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Adaptation of climate-responsive building design strategies and resilience to climate change in the hot/arid region of Khartoum, Sudan

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ABSTRACT

Climate change has become one of the most discussed topics in recent decades. Indices show climate alterations have occurred in Khartoum, Sudan, resulting in uncomfortable and challenging-to-manage indoor conditions. In this study, Khartoum's climate data from 1981 to 2015 was analyzed and compared to identify trends in temperature, precipitation, and sand-dust storm intensification. Metronome Company created Khartoum's hourly weather file from averages of basic climate parameters available for 1996 to 2015 and Meteonorm 7.2.1 calculated an hourly climate file for Khartoum in 2070. These figures were then related to design characteristics and lifecycles of local buildings. To counter 2070 climate conditions, resilient design strategies were evaluated to optimize thermal comfort for building users and minimize energy usage today and in the future. A comparison of design strategies from the year 2015 to those for 2070 discovered that strategies must shift to more active-cooling by the year 2070 when natural ventilation and active heating will no longer be beneficial design strategies during all seasons. While two-stage evaporative cooling is the most strategic for all of Khartoum's seasons, more resilient passive-design strategies should be adapted for use with Khartoum's underutilized renewable resources to reduce future active-cooling demand and optimize thermal comfort.

1. Introduction

In the recent decades, numerous scientists have expressed great concern about climate change and global warming, considering them to be serious threats to mankind and the natural environment (Omondi et al., 2014). The year 2015 AD was the hottest year since 1850 AD though the previous three decades the global weather conditions had been considered the hottest since 1850 AD. In 2015 alone, the global temperature increased 0.75 °C,[1] which was greater than the cumulative increase from 1961 to 1990 AD [URL1, 2019]. These global temperature increases are caused by the accumulation of carbon dioxide emissions in the atmosphere which result, in the majority, from the burning of fossil fuels, therefore, there is urgent need to reduce this increased emissions through reducing reliance on fuel fossil consumption and relay more on renewable energy to achieve sustainable development. According to the 2013 report from Intergovernmental Panel on Climate Change (IPCC), if the current emissions trends continue without finding sustainable solutions, the average rate of global temperature increase over the years 2081 to 2100 AD will reach 4.8 °C which is greater than the cumulative of 1986 to 2005 [URL2, 2013].

Global warming is also projected to negatively influence global precipitation, evaporation, and evapotranspiration rates [Schlosser & Houser, 2007; Hu et al., 2017]. Alongside recent reports documenting climate change occurrences at global, regional and local levels, these dangers to human and environmental wellbeing demand that the international community respond with urgency and take appropriate measures to reduce greenhouse gas emissions. This would however, require researchers to find appropriate, climate-responsive design solutions to anticipate and respond to future climate change. Success cannot be achieved by merely altering individual behaviors and consumption patterns; to sufficiently reduce energy emissions there is a need for global adoption of new low-carbon technologies which help to decarbonize the byproducts of energy use [Remund, Lang, & Kunz, 2013; Spence & Pidgeon, 2009]. Comprehending climate-related behaviors and patterns at global, regional, and local levels is essential for designers in the field of environmental science; with this knowledge they can develop such things as early warning systems and counters to future climate challenges.

Abbreviations: IPCC, Intergovernmental Panel on Climate Change; HVAC, heating ventilation and air-conditioning; ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers; PMV, predicted mean vote; WBD, Wet Bulb Depression; WBT, Wet Bulb Temperature

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[1] For Sudan, and Africa in general, climate change effects include a 0.20 °C increase in temperature across the entire continent [El sheikh, 2015].

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The design of climate-responsive buildings may meet these challenges and has the potential to collectively change user behaviors during climate extremes. Hansen, Sato, and Ruedy, (2012) and Kamal (2013) describe this adaptability of buildings as a phenomenon of climate change [Snow & Deo Prasad, 2011; Hansen et al., 2012; Kamal, 2013]. It is imperative for researchers in the fields of the built environment to proffer sustainable solutions for this dilemma at urban, regional, and global levels [Charter, 2007]. Failing to incorporate sustainable design strategies will lead to poorly naturally ventilated buildings in the future which experience longer overheating duration in summer season. Hence, this will demand the use of air-conditioning system to achieve acceptable thermal comfort level [Watkins, Palmer, Kolokotroni, & Littlefair, 2002; Roberts, 2008].

The aims of this study are to reveal conditions affecting thermal comfort in Khartoum, Sudan, and suggest relevant building-design strategies to increase resilient to both current and projected climatic conditions. To achieve this, the objectives include discovery of climate change trends through evaluation of Khartoum's climate data from 1981 to 2015; understanding how climate trends affect buildings; and identifying ways to enhance future thermal comfort of building users in Khartoum.

2. Study area: Khartoum, Sudan

The city of Khartoum, Sudan, was founded in 1820 CE and later became the capital of this northeastern African country. The city's name derives from its shape which resembles an elephant trunk (Al Khartoum in Arabic). Its development is focused around 15°33′06″ N latitude, 32°31′56″ E longitude and it averages 380 m above sea level. The city's location in the center of the country coupled with its strategic position at the confluence of the Blue and White Nile Rivers made it one of the most important cities in the Sudan. [Shakurov, Elamin, & Zebilila, 2016; Awad & Hussein, 2006]. The Central Bureau of Statistics of Sudan (CBSS) estimated Khartoum's population at 6.5 million in 2013 with a 2.7% rate of annual increase [URL3, 2014]. The study area of Khartoum City shows in (Fig. 1)

Fig. 2. sand-dust-storm-Khartoum-Sudan-video-haboob-climate-change.
(Source: Google available at: http://www.express.co.uk/news/world/812366.

In the Köppen classification system of climate, Khartoum is located in a hot arid desert zone. According to Elagib, Ahmed, and Mansell, (2000), Khartoum's three seasons are winter (a dry season covering November through February), summer (a hot season starting in March and extending to May), and autumn (a wet season lasting from June to October) [El sheikh, 2015].

A notable phenomenon of Khartoum's climate is sand-dust storms which prevail throughout central Sudan. These storms are categorized into three distinct types. A haboob is a dust storm associated with clouds, as in (Fig. 2) and is caused by winds moving from north-northeast to south-southwest. They usually occur in desert regions of the northern hemisphere between April and September, and reach maximum intensity during June. Each haboob can last from 30 min to several hours. A second dust storm occurring in Khartoum involves steep pressure gradients caused by south-southwest winds from intertropical fronts. These prevail from May to October. Khartoum's third type of sand-dust storm is caused by north-northeast trade winds crossing the greater desert between February and April. These winds are accompanied by fine particles [Bakr, 1988; Miller et al., 2008]

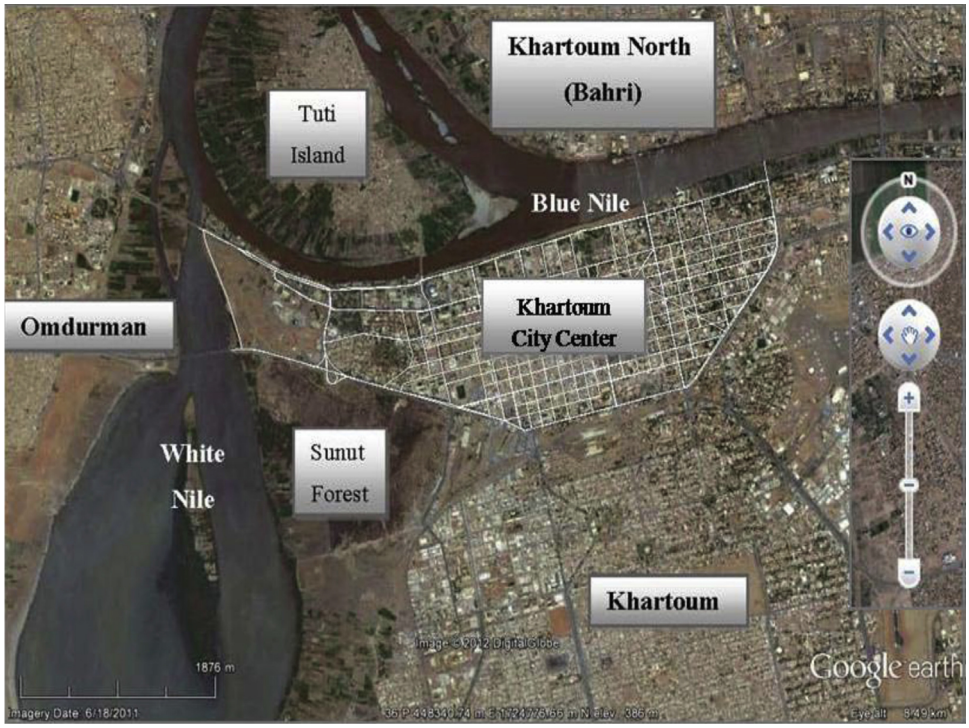

Fig. 1. Geographical location of Khartoum City Center.
(Source: Map adapted from: Google Earth)

which create sincere design challenges addressable through filtration of the air entering buildings.

Three studies[2] explain how environmental degradation attributed to climate change has happened in Khartoum, during prior decades. For example, Omer, Elhassan, and Mohammed, (2015) indicate that vegetative cover of Khartoum was reduced by human activity after climate-induced urban migrations starting in 1993 as a result of drought in some areas in Sudan. Activities associated with urbanization and reductions in vegetation include housing development and increases in seasonally-fallow or nutrient-poor agricultural lands due to food-production pressures [Omer et al., 2015]. Secondly, trends analysis of Khartoum rainfall data collected from Khartoum Meteorological Station between 1900 and 1980 shows a significant decrease in rainfall, an indication of climate change [Altahir, 1988]. Finally, the only known effort to analyze Khartoum's building design strategies was carried out by Saeed in 1989, when he calculated annual thermal comfort related to the various design strategies.

3. Research methodology

The methodology of this research is based on case-study problem solving in which Khartoum's climate data from 1981 to 2015 was analyzed via a linear trends method. Trend is a substantial change that occurs to the time-series value of a parameter or variable and is recognized through statistical parametric or non-parametric means. Time series verse data is a method suitable for climate change issues. It enables researchers to perceive trends in a specified time frame [Shi & Xiangde, 2008]. Parameters considered for this study include monthly average relative humidity, temperature, wind speed, and rainfall. Regression analysis was performed on these parameters in the following steps.

Linear trends for all climatic parameters considered in this study were drawn based on seasons of the year in order to understand the increasing or decreasing trend of the mentioned parameters from 1981 to 2015. Normalized monthly averages were performed for all parameters using $Z = (x - \mu) / (\sigma / \sqrt{n})$ where Z represents the normalized data, X is the value to be normalized, μ is the mean of the value to be normalized, σ is the standard deviation, and n equals the number of values. The importance of normalizing data is to get rid of units. Here the weight values are assigned to the normalized data to aid comparison.

Then the four parameters are plotted against each other and against R-square value to understand the extent to which these parameters are significant. When R-square value approaches one this indicates a significant relationship; if otherwise, the relationship is said to be insignificant. Once linear trend lines are fitted, the R-square values obtained.

Khartoum weather files were calculated using the average climate data of the city between the years 1996–2015. Since weather files are based on hourly values of climate parameters, and as is the case in most developing countries, Khartoum metrological Station has no records of hourly climate data, Meteonorm 7[3] was used to calculate Khartoum weather files. Future predicted energy usage plus hourly weather files for the year 2070 CE in Khartoum were calculated by Meteonorm 7.2.1[4] .

With the climate data projections for 2070, future design strategies for Khartoum can be proposed to achieve sustainable and climate responsive building designs. The design strategies adapted in this research work for both the contemporary and future climate of Khartoum. These strategies were recommended by a computer design tool referred to as Climate Consultant 6.0 and known to be a very dependable [URL4 and Milne, 2019].

4. Climate data analysis of Khartoum, Sudan

For climate parameters from 1981 to 2015, trend analysis was evaluated in order to observe variations which occur in trend equations and R-square values of climate parameters on a seasonal basis. Monthly averages of the relative humidity, temperature, wind speed, and rainfall were considered and the results are shown in (Table 1).

4.1. Season-based trends analysis

4.1.1. Dry season (Nov, dec, jan and feb)

The winter dry season in Khartoum is characterized by very low relative humidity (RH); RH values between 8% and 10% are common. The trend analysis indicates that RH has been decreasing annually by 0.02% and temperatures during the dry season exhibit an annual increase of 0.1 0 °C. Reductions in plant cover, as revealed by Mohamed and Babiker (2015), account for both the decrease in RH and the seemingly contradictory increase in rainfall [Omer et al., 2015]. Rainfall's annual increase during the dry season is not a normal phenomenon for Khartoum and therefore invariably a sign of climate change.

Variations in climate parameter's for the dry season are shown in Table 1. Trend analysis of Khartoum climate data from 1981 to 2015 shows that climate change has occurred. While the dry season in Khartoum is historically characterized by northern winds which pass through the greater desert and are accompanied with dust and sand storms, proven climate change will also make the occurrence of dust and sand storms more frequent than ever before.

4.1.2. Hot season (march, april and may)

The hot summer season in Khartoum has low relative humidity with some temperatures exceeding 40 °C. Trend analysis of climate parameters displays an annual decrease of RH by 0.07%, an annual increase of temperature by 0.010 °C, an annual decrease of wind speed by 0.002 m per second, and an annual increase of rainfall by 0.01 mm.

These results reveal climate changes during the 1981–2015 hot seasons and projections mean more extreme temperatures and lower RH and wind speeds in Khartoum's future hot seasons. Relatedly, Yousif and Hashim (2013) disclosed that Khartoum was the hottest city in the world during 2009.

4.1.3. Wet season (June, jul, aug, sept and oct)

Khartoum's autumn wet season includes August as its wettest month. Trend analysis of wet season parameters from 1981 to 2015 provides four findings. Even though there was an annual reduction of rainfall by 0.004 mm during this season, the city witnessed severe flooding due to extreme rainfall events in 1988, 2003, 2007, and 2009. Despite the reduction in rainfall, an annual increase of RH by 0.2% was observed. These alone could be considered as sign of climate change but Khartoum also experienced an annual increase in temperature of 0.02 °C and an annual reduction in wind speed by 0.002 m per second.

The trend analysis' decrease in wind speed, increase in temperature, and decrease in rainfall shows that climate change has happened during the period from 1981 to 2015.

4.2. Correlation of climate parameters

The correlations between climate parameters are derived from normalized data such that all parameters are dimensionless and can be assumed to have similar importance. The normalization of the study parameters (humidity, temperature, wind speed, and rainfall)

[2] Information about past, contemporary, and projected climate change for the Greater Horn of Africa, which includes Sudan and Khartoum, is limited [Osman, Sevinc, & Hancer, 2019].

[3] Meteonorm 7 is a well-known source of climate data based in Bern, Switzerland which can produce reliable climate data for any location in the world [Roberts, 2008; Roberts, 2008;].

[4] Meteonorm 7.2.1 can provide future hourly weather files up to the year 2100.

Table 1
Trends Equation with R-square values for Relative Humidity, Temperature, Wind speed & Rain fall for Khartoum city from 1981 to 2015.

Parameter	Season	R-square value	Equation	Comment
Humidity (%)	Dry	0.0047	y = -0.0163x + 57.349	Decrease 0.02
	Hot	0.0529	y = -0.0669x + 149.86	Decrease 0.07
	Wet	0.0883	y = 0.1792x - 320.14	Increase 0.2
Temperature (C°)	Dry	0.3704	y = 0.0619x - 96.268	Increase 0.1
	Hot	0.0046	y = 0.005x + 23.999	Increase 0.01
	Wet	0.0132	y = 0.0094x + 11.418	Increase 0.01
Wind speed (m/s)	Dry	0.0008	y = 0.0023x - 0.106	Increase 0.002
	Hot	0.0214	y = -0.0094x + 23.08	Decrease 0.01
	Wet	0.0006	y = -0.0018x + 7.6367	Decrease 0.002
Rain Fall (mm)	Dry	0.0042	y = 0.002x - 3.999	Increase 0.002
	Hot	0.0009	y = 0.0079x - 13.873	Increase 0.01
	Wet	8E-06	y = -0.0041x + 30.474	Decrease 0.004

Trends Equation with R-square values for Relative Humidity, Temperature, Wind speed & Rainfall for Khartoum city from 1981 to 2015.

determines there are no significant correlations between them since the R-square values do not approach one. The following (Table 2) shows the correlation of studied parameters.

5. Climate-responsive building-design strategies adapted

5.1. Comfort model

The adaptive comfort model used in this study assumes that buildings are naturally ventilated and occupants can close and open windows according to their thermal desires. Hence, building users' thermal response will depend in part on the outdoor climate and may have a wider comfort range than those in buildings with centralized heating ventilation and air-conditioning (HVAC) systems. For the ASHRAE Standard 55 model, there must not be any mechanical cooling system nor does this method apply if a mechanical heating system is in operation [URL5, 2010; Rubio-Bellido, Pulido-Arcas, & Cabeza-Lainez, 2015]. Furthermore, the model assumes that occupants are sedentary (1.0–1.3 metabolic activity) and adapt their clothing according to expected thermal conditions.

This comfort model is suitable for application in the hot and arid climate of Khartoum, Sudan. Comfort zone plotting in a psychometric chart is a well-known design tool used to plan in the early design stages for optimum thermal comfort of building occupants. Numerous researchers in the field of building and sustainable environment have undertaken these issues [Nguyen & Reiter, 2014]. Meteonorm Company calculated climatic hourly weather files for 1996 to 2015 from average climatic data of Khartoum. Subsequently, the files were processed through Climatic Consultant 6.0. ASHRAE Standard 55 model was selected in order to calculate contemporary thermal comfort for Khartoum. When ASHRAE Standard 55-2010 adapted for natural ventilation in Khartoum, annual thermal comfort is achieved in 2119 h out of the 8760 h in a year (or 24.2% of the year) as shown in (Table 3).

Based on monthly thermal comfort values, it was observed that it is most difficult to achieve thermal comfort using this model during Khartoum's hot season. May then April are the least comfortable months. The highest thermal comfort from natural ventilation is achieved in the dry winter season with November having the highest thermal comfort (32.9%) of all dry season months.

5.2. ASHRAE standard 55 and current handbook of fundamental model

The adaptive comfort model used in this study is based on American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55 and its current handbook of thermal comfort. This model considers dry bulb temperature, clothing level (clo), metabolic activity (met), air velocity, humidity, and mean radiant temperature (MRT). It is assumed that MRT and dry bulb temperature are similar. The zone in which most people are comfortable is calculated using the Predicted Mean Vote (PMV) model. Moreover the adaptive comfort model reflects that in residential buildings, which are predominantly naturally ventilated and people adapt clothing in a way to match seasonal conditions and feel comfortable in higher air velocities. So, they have wider comfort ranges than those in buildings using central air-conditioning systems [Altahir et al., 2013]

In accordance with these specifications, solar control is one of the most valuable strategies in modifying thermal comfort in climates like Khartoum's. Sudanese vernacular architecture provides excellent techniques for managing solar heat gain: the design of a roof to shade itself; and rotational use of space where open and semi-open spaces are used for instance for relaxation and sleeping during different periods. Besides the mentioned strategies, other commonly adapted design strategies are two-stage evaporative cooling, natural ventilation, internal heat gain, dehumidification, and active cooling. It is not possible to achieve 100% thermal comfort without using mechanical cooling systems which increase thermal comfort by 27.1% of the total comfort. Through combination of these thermal-comfort strategies with a mechanical cooling

Table 2
Correlation Table shows R-square values of normalized parameters (Relative Humidty, Temperature, Wind speed & Rain fall) based on the three seasons of Khartoum city of Sudan.

Parameters	Season	Humidity (%)			Rain Fall (mm)			Wind Speed (m/s)			Temperature (C°)		
		Dry	Hot	Wet	Dry	Hot	Wet	Dry	Hot	Wet	Dry	Hot	Wet
Humidity	Dry	X											
(%)	Hot	0.48	X										
	Wet	0.15	0.12	X									
Rain Fall	Dry	0.0006	0.016	0.011	X								
(mm)	Hot	0.016	0.02	0.06	0.14	X							
	Wet	0.09	0.14	0.35	0.002	0.002	X						
Wind Speed	Dry	0.07	0.02	0.001	0.0004	0.009	0.003	X					
(m/s)	Hot	4E-05	0.004	0.0005	0.003	0.05	0.0003	0.47	X				
	Wet	0.0008	0.005	0.006	0.03	0.09	0.009	0.48	0.36	X			
Temperature	Dry	0.04	0.003	0.02	0.02	0.07	0.003	0.01	0.007	0.03	X		
(C°)	Hot	0.003	0.03	0.04	0.002	0.02	7E-05	0.02	5E-05	0.01	0.03	X	
	Wet	0.009	0.04	0.03	0.001	0.02	0.0004	0.0001	9E-05	1E-06	0.001	0.12	X

Correlation table shows R- square values of normalized parameters (Relative Humidity, Temperature, Wind speed & Rainfall) based on the three seasons of Khartoum city of Sudan.

Table 3
Adaptive comfort Model in ASHRAE Standard 55-2010 applied in Khartoum city of Sudan for the year 2015.

Months	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Comfort %	24.2%	28.4%	27.8%	28.1%	26.4%	6.3%	0%	18.1%	33.2%	30.8%	30%	32.9%	28.4%
Comfort hrs.	2119	211	187	209	190	47	0	135	247	222	223	237	211
Total hrs.	8760	744	672	744	720	744	720	744	744	720	744	720	744

Adaptive Comfort Model in ASHRAE Standard 55—2010 applied in Khartoum city of Sudan for the year 2015.

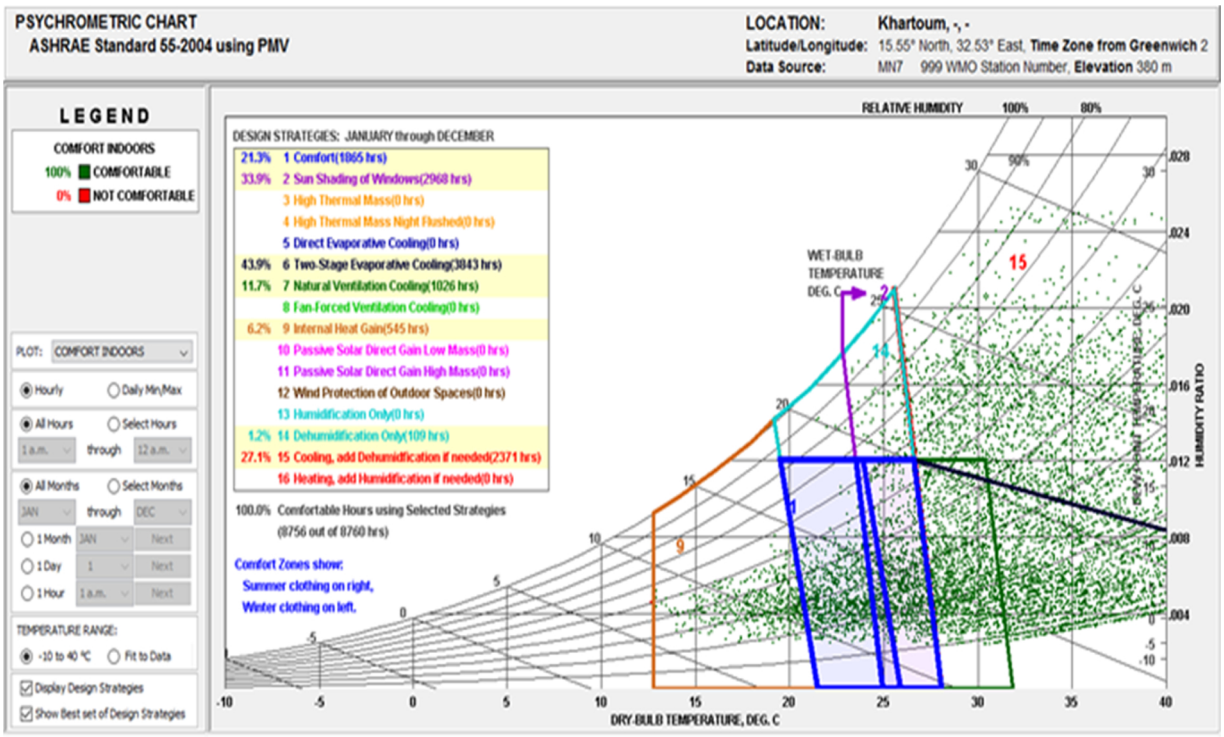
PSYCHROMETRIC CHART
ASHRAE Standard 55-2004 using PMV
LOCATION: Khartoum, -, -
Latitude/Longitude: 15.55° North, 32.53° East, Time Zone from Greenwich 2
Data Source: MN7 999 WMO Station Number, Elevation 380 m
LEGEND
COMFORT INDOORS
100% COMFORTABLE
0% NOT COMFORTABLE
DESIGN STRATEGIES: JANUARY through DECEMBER
21.3% 1 Comfort(1865 hrs)
33.9% 2 Sun Shading of Windows(2968 hrs)
3 High Thermal Mass(0 hrs)
4 High Thermal Mass Night Flushed(0 hrs)
5 Direct Evaporative Cooling(0 hrs)
43.9% 6 Two-Stage Evaporative Cooling(3843 hrs)
11.7% 7 Natural Ventilation Cooling(1026 hrs)
8 Fan-Forced Ventilation Cooling(0 hrs)
6.2% 9 Internal Heat Gain(545 hrs)
10 Passive Solar Direct Gain Low Mass(0 hrs)
11 Passive Solar Direct Gain High Mass(0 hrs)
12 Wind Protection of Outdoor Spaces(0 hrs)
13 Humidification Only(0 hrs)
1.2% 14 Dehumidification Only(109 hrs)
27.1% 15 Cooling, add Dehumidification if needed(2371 hrs)
16 Heating, add Humidification if needed(0 hrs)
100.0% Comfortable Hours using Selected Strategies
(8756 out of 8760 hrs)
Comfort Zones show:
Summer clothing on right,
Winter clothing on left.
RELATIVE HUMIDITY
WET-BULB TEMPERATURE DEG. C
HUMIDITY RATIO
DRY-BULB TEMPERATURE, DEG. C
PLOT: COMFORT INDOORS
Hourly
Daily Min/Max
All Hours
Select Hours
All Months
Select Months
TEMPERATURE RANGE:
-10 to 40 °C
Fit to Data
Display Design Strategies
Show Best set of Design Strategies

Fig. 3. Psychometric chart with climate responsive Design strategies applied in Khartoum city. Climate Consultant tool 6.0.
(Source: generated from climate consultant 6.0 by the Author)

system 72.9% (6385 h out of 8760 h) of thermal comfort can be achieved (see Fig. 3). The comfort range without using any design strategies is reduced to 21.3% and 24.2% thermal comfort is achieved by using the adaptive comfort model. The little variations achieved through this research contributed to global horizontal solar radiation control and relative humidity modification with adoption into the thermal comfort model. Changes to relative humidity may also be influential in Khartoum-type climates.

When appropriate shading of windows is applied it increases thermal comfort by 33.9% (zone 2). The strategies of internal heat gain (zone 9), dehumidification only (zone 14), active cooling (zone 15), and natural ventilation (zone 7) improve thermal comfort by 6.2%, 1.2%, 27.1%, and 11.7% respectively. Although two-stage evaporative cooling has no direct impact on thermal comfort and it contributes up to 43.9%. If evaporative cooling is not used, it would increase active cooling rate from 27.1% to 59.5%. This shift means two- stage evaporative cooling should be adapted to reduce any discomfort that may occur and to reduce active cooling load. The combined use of both active cooling and two-stage evaporative cooling is valuable in Khartoum because together they can improve thermal comfort up to 59.5%.

A classification of design strategies for each season is shown in (Table 4). A thermal comfort of 41.7% can be achieved in the dry season, 22.9% in the hot season and 4.3% wet season.

In the dry season, two-stage evaporative cooling is the most influential strategy. It has directs impacts on thermal comfort and contributes about 40.9% (1179 h out of 8760 h). Window shading is most important from 10:30 AM to 3:00 PM during this season. Active heating constitutes 0.1%, and it could be replaced by increasing building thermal mass.

In the hot season about 22.9% thermal comfort can be achieved without adapting any design strategies. To achieve optimal thermal comfort, window shading from 9:00 AM to 5:00 PM is needed to protect building interiors from overheating. A combination of cooling, dehumidification (active cooling), and two-stage evaporative cooling is better even though two-stage evaporative cooling contributes 72.8% (1608 h out of 8760 h) because it doesn't have direct effect on thermal comfort in this season. If not used it would increase cooling by dehumidification (active cooling) from 2.1% (47 h) to 75% (1655 h). Moreover internal heat gain is another strategy that should not be neglected.

The wet season is one of the hottest seasons in Khartoum; As a result, a thermal comfort of only 4.3% can be achieved without using any strategy. Window shading is most advantageous from 8:30 AM to 5:00 PM to avoid overheating. Cooling and dehumidification (active cooling) are the most important strategies to achieve thermal comfort during the wet season; they constitute 63.3% (2324 h) and directly affect thermal comfort. It should be used congruently with two-stage evaporative cooling. If two- stage evaporative cooling is not used, the cooling demand would increase from 63.3% (2324 h) to 85% (3122 h). Dehumidification only contributes about 3% to thermal comfort in the wet season but directly affects thermal comfort. Natural ventilation is

Table 4
Classification of design startegies on seasonal basis for Khartoum city of Sudan for the year 2015.

Design Strategies	Dry Season	Hot Season	Wet Season
Comfort	41.7 %(1200 h)	22.9%(506 h)	4.3% (159 h)
Sun shading	30.1% (867 h)	35.9% 792 h)	35.8%(1313 h)
2 stage evaporative cooling	40.9% (1179 h)	72.8% (1608 h)	28.8% (1056 h)
Internal heat gain	17.3% (498 h)	2.1% (47 h)	–
Heating, Add Humidification	0.1% (4 h)	–	–
Cooling Add dehumidification	–	2.1%	63.3%(2324 h)
Dehumidification only	–	–	3% (109 h)
Natural Ventilation	–	–	7.7%(0 h)

Classification of design strategies on seasonal basis for Khartoum city of Sudan for the year 2015.

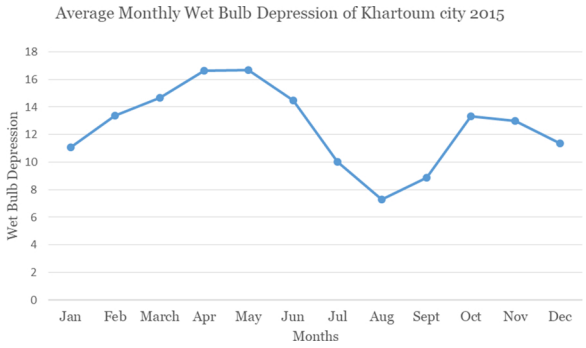

Fig. 4. Illustrates average monthly wet bulb depression (WBD) in Khartoum city of Sudan 2015. Data is obtained from EPW weather file of Khartoum city.

an applicable design strategy only in the wet season.

Finally, precautions should be taken to control sand-dust storms which occur at different times of day throughout the year. Miller et al. (2008), after observing Haboobs in Khartoum's central district for eight years, found that dust-storm wall height could exceed one kilometer and each storm could last from 30 min to several hours. Moreover, these storms occurred 50% of the days between May and June and 70% of days from July to September [Miller et al., 2008]. For these reasons, when air is admitted into buildings, it should pass through a series of filters. This can be done at the urban scale by planting trees in a buffer surrounding the city, and at building scale by installing a series of filters in air inlet locations.

6. Passive cooling strategies adaptable in Khartoum, Sudan

Adapting passive cooling measures in building design and construction denotes utilizing any design techniques or feature that help in providing optimum living condition for building dwellers without the need for using power [Taleb, 2014]. Passive strategies using in building has become more popular after 1970s energy crisis. In order for the passive cooling strategies to operate effectively climate should critically be analyzed. The board strategies that are to be discussed in this research are heat-loss promotion and heat removal strategies'.

6.1. Heat-loss promotion strategies

Heat loss-promotion can provide optimal thermal comfort for buildings occupants if properly applied. For this strategy to function best, the industry needs more developed techniques related to heat dissipation. Heat dissipation utilizes naturally-existing air pressure and the pressure differences between inside and outside a building to move hot air away. This technique can be broadly categorized into natural ventilation and natural cooling.

6.1.1. Evaporative cooling

Evaporative cooling is a heat and mass transfer process that uses water evaporation for air cooling. In this process a large amount of heat is transferred from air to water and consequently the air temperature decreases. The three types of evaporative coolers are direct evaporative coolers, in which the working fluids (water and air) are in direct contact; indirect evaporative coolers, where a surface/plate separates the working fluids; and a combined system of direct and indirect evaporative coolers with or without other cooling cycles.

Evaporative cooling, as the name implies, depends on climatic conditions than more active cooling [El-Refaie & Kaseb, 2009]. In order for this system to function efficiently, climate parameters such as wet bulb temperature, dry bulb temperature, and wet bulb depressions need to be analyzed.

6.1.1.1. Wet Bulb Depression (WBD). Wet Bulb Depression (WBD) is one of the most influential parameters determining the efficiency of evaporative cooling. It is defined as the difference between Dry Bulb Temperature (DBT) and Wet Bulb Temperature (WBT). As WBD increases, the efficiency of evaporative cooling increases [Hui & Cheung, 2009].

6.1.1.2. Major properties of Wet Bulb Depression in Khartoum, Sudan. Analysis of average monthly Wet Bulb Depression of Khartoum data (plotted in Fig. 4) shows that wet bulb depression (WBD) is highest in the month of May thus evaporative cooling is a very effective strategy during this month. The month of August has the lowest WBD paired with low efficiency of evaporative cooling strategies, therefore active cooling is the more effective strategy recommended by Climate Consultant 6.0 for August. Furthermore, by comparing evaporative cooling efficiency of 2015 and 2070 (plotted in Fig. 5) shows that there is slid decrease in the efficiency of evaporative cooling in the dry season of 2015 compared to 2070 while efficiency in hot season remain the same for both 2015 and 2070.Pertaining wet season, evaporative cooling efficiency is more efficient in 2070 than 2015.This might be attributed to climate change of Khartoum.

Efficiency analysis of evaporative cooling strategies on a seasonal basis (plotted in Fig. 5) that the strategy has the highest efficiency for the year 2015 in the hot season, while it has the lowest efficiency in the

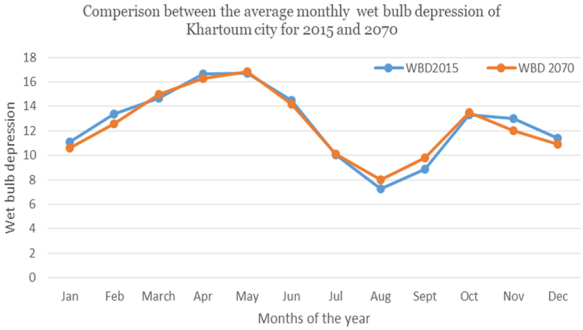

Fig. 5. Illustrates average monthly wet bulb depression (WBD) in Khartoum city of Sudan. Data is obtained from EPW weather file of Khartoum city.

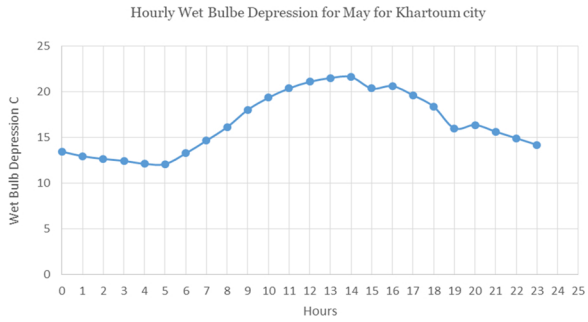

Fig. 6. Illustrates average hourly wet bulb depression (WBD) for Khartoum city in month of May. Data is obtained from EPW weather file of Khartoum city.

wet season. For the year 2070 the strategy efficiency seasonally is same as 2015.

Also in (Fig. 6) the analysis of hourly Wet Bulb Depression for the month of May, which is one of the hottest months in Khartoum, indicates that WBD changes over the course of the day and is higher between 8:00 am and midnight (14.7 °C). As such, evaporative cooling works more efficiently during these times of day. By comparing the efficiency of 2015 and 2070 as in (Fig. 7) there is general decrease in the efficiency in 2070 and it is hourly efficiency is same as 2015.However this give indication that active cooling is highly needed in 2070 compared to 2015.

6.1.1.3. Two-stage evaporative cooling. Several suitable passive and active cooling strategies can be applied to buildings in Khartoum. Based on Climate Consultant 6.0 analysis, two-stage evaporative cooling seems the most suitable cooling strategy for Khartoum in both dry and wet seasons of the year.

Two-stage evaporative cooling comprises indirect evaporative cooling in stage one which provides precooled air to the direct evaporative cooling system in stage two [Sharag-Eldin, 1988]. ASHRAE makes it known that two-stage evaporative cooling can use 60%–70% less power than a normal air-conditioning system. This makes two-stage evaporative cooling an effective, sustainable, and energy-efficient cooling strategy. The success of this cooling strategy is dependent on the WBD that occurs between wet bulb temperature and dry bulb temperature [Ambade, 2015]. The way two-stage evaporative cooling systems operate shows in (Fig. 8)

As noted before, Khartoum's climate is characterized as having low relative humidity; consequently, this cooling strategy can provide thermal comfort for building users. In order for this cooling strategy to function best, 100% external air movement should be guaranteed. Without external air movement, indoor relative humidity would increase beyond the comfort level of building users. According to Sharag-Eldin (1988), during the hot season of the year in Khartoum, two-stage evaporative cooling can reduce dry bulb temperature to 29 °C and

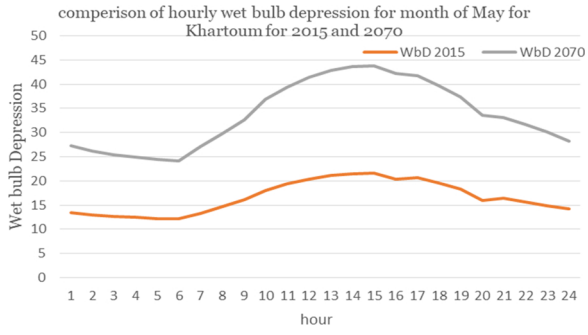
comperison of hourly wet bulb depression for month of May for Khartoum for 2015 and 2070
WbD 2015
WbD 2070
Wet bulb Depression
hour

Fig. 7. Shows the comparison between hourly wet depression (WBD) for Khartoum city for the month of May 2015 and 2070. (Data is obtained from EPW weather file of Khartoum city).

increase relative humidity to 60% provided outside air blends with inside air upon entry.

Furthermore, two-stage evaporative cooling is an appropriate design strategy in Khartoum during its dry season. When building envelopes are insulated, it increases thermal comfort by 17.3% or 498 h (see appendix 1). During the hot season, buildings with appropriate thermal insulation may improve comfort zones by 2.1% (47 h) reducing the demand for active cooling (see Appendix 2). The wet season has the least efficient use of two-stage evaporative cooling among the seasons due to relatively high humidity; natural ventilation is the best strategy for increasing the comfort zone during this season (see appendix 3).

6.1.1.3.1. Advantages of two-stage evaporative cooling. There are five advantages of two-stage evaporative cooling. It is energy and cost efficient and more appropriate in areas where direct evaporative cooling is insufficient. It consumes half as much energy as air-conditioning systems use and its construction is more cost efficient. It provides better thermal comfort than compressor-based systems and can replace mechanically-refrigerated cooling systems. It provides 100% cooling and internal air quality is improved through the insertion of fresh air; 25–40 air changes per hour makes it similar to natural ventilation. This cooling strategy uses evaporation which makes it environmentally friendly.

6.1.1.3.2. Disadvantages of two-stage evaporative cooling. There are four disadvantages of two-stage evaporative cooling. It is inefficient in coastal areas where relative humidity is high. There are significant temperature variations in the cooled space throughout the year depending on the prevailing ambient dry and wet bulb temperatures [Ambade, 2015]. It requires frequent maintenance. The entire system may fail in situations when there are water shortages and power failures such as are common in hot dry areas like Khartoum [Ambade, 2015].

6.1.2. Natural ventilation

Natural ventilation is one of sustainable cooling strategies relied upon to achieve thermal comfort. In hot and dry climates when outside temperature is beyond tolerable levels, it is more appropriate to close windows until temperatures decrease to more acceptable levels [Aynsley, 2014]. The potentiality for using natural ventilation strategies depends significantly on the local climate [Chen, Tong, & Malkawi, 2017]. Natural ventilation is not a best practice for all seasons in Khartoum but is appropriate during the wet season. In this season, the city experiences frequent rain showers. According to Butera, Adhikari, and Aste, (2015), in most hot, dry regions the daytime temperature is above 26 °C and relative humidity is below 50%. Under these conditions daytime natural ventilation is not beneficial and appropriate solar control is essential to reduce overheating. If night temperatures are below 20 °C, natural ventilation strategies can be utilized to admit cooler air into the building [Butera et al., 2015]. Night ventilation strategies function well with appropriate building thermal mass in Khartoum. Night coolness occurs as a result of increased wind movement and humidity rising from the Nile River. (Fig. 9) illustrates night ventilation.

Natural ventilation in Khartoum is utilized in the daytime during dry seasons and during the night in hot seasons. However, the best season to use natural ventilation is the wet season. The best time of the day to employ natural ventilation in the wet season is from midnight until 6:00 AM because of increased humidity and wind speed. Natural ventilation is also efficient though less so from 6:00 AM until noon as illustrated in (appendix 3).

Building form and position and size of windows dictate operational efficiency of natural ventilation. Single-sided ventilation, cross-ventilation, and stack ventilation are the most common ventilation principles providing thermal comfort for Khartoum's building users [Kleiven, 2003]. It is possible to combine all of these principles in one building to better exploit wind movements (see Fig. 10).

Furthermore, Shakurov et al. (2016) promoted simultaneous exposure of microclimate effects of natural ventilation on temperature,

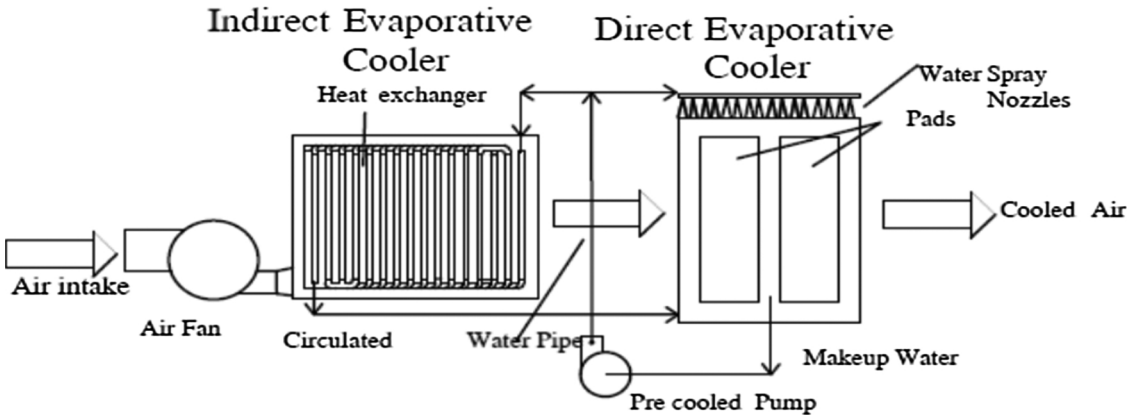

Fig. 8. Illustration of two-stage evaporative cooling system [adapted from Al-Juwayhel, et al. (2004)].

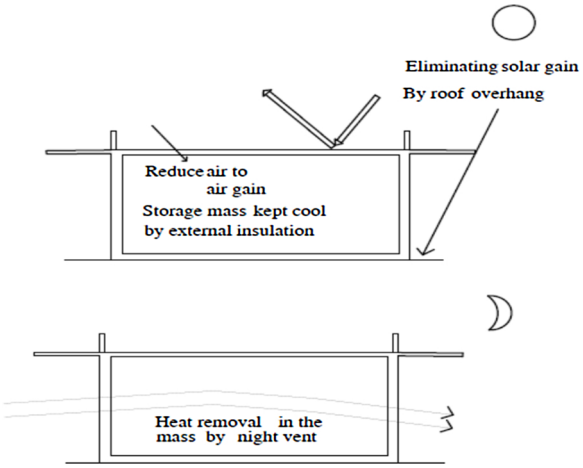
Eliminating solar gain
By roof overhang
Reduce air to air gain
Storage mass kept cool by external insulation
Heat removal in the mass by night vent

Fig. 9. Illustrates night ventilation in Khartoum city.
Source:

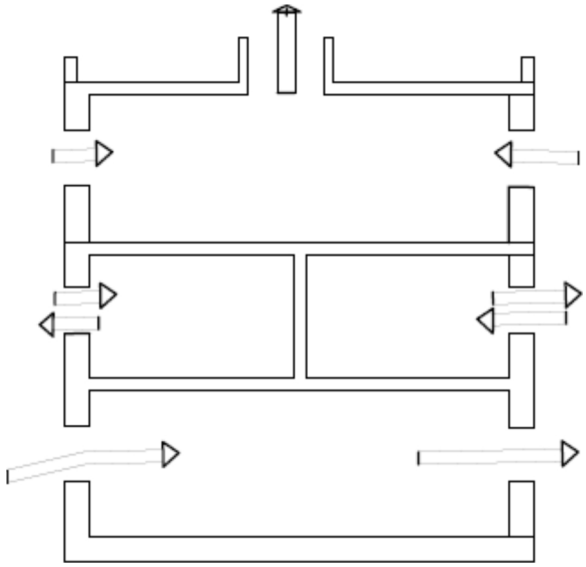

Fig. 10. Sketch shows combination of cross, one sided and stack effect ventilation in one building.

humidity and wind speed. The temperature difference between 8:00 AM and 5:00 PM in green areas of sandy-soil regions ranges from 15 °C to 20 °C while those in loamy-soil and asphalt regions can reach 45 °C [Shakurov et al., 2016]. Appropriate architectural and urban design strategies help improve microclimate conditions of the city.

Finally, for natural ventilation, Sudan is blessed with abundant renewable energy sources in the forms of wind, solar, and water. When adequately utilized, these provide prime cooling solutions for buildings. However, in order to achieve maximum benefit from natural ventilation there are various building design elements (solar chimneys, wind towers, and double-skin façades) that stimulate air movement [Brager & de Dear, 2000].

6.1.3. Solar chimneys

Utilization of passive-solar strategies in building design is a sustainable solution capable of reducing energy usage as much as 25% [Godoy-Vaca, Almaguer, Martínez, Lobato, & Palme, 2017]. Solar chimneys are one passive-solar strategy that exploits renewable energy to improve a buildings' interior air quality [Mehani & Settou, 2012]. It uses a combination of solar stack-assisted and wind-driven ventilation. The solar chimney is most appropriate for low-rise buildings which include about 80% of buildings in Khartoum. Double-skin façade are a more appropriate solar strategy for high-rise buildings.

In both cases, air inside the chimney or gap expands as a result of solar heating and become less dense. The lighter, hotter air rises out of the top vent dragging cooler breezes from the bottom through windows. These strategies can be complemented further by outside wind pressure, by pressure differences between the interior and exterior air temperature, and by inducing greater pressure difference via temperature differences and increased stack height [Tan & Wong, 2013]. These strategies are appropriate in almost all season of the year if located and designed in accordance with location and direction of solar radiation.

The following (Fig. 11) illustrates how the solar-chimney strategy when used for cooling can be enhanced when used in combination with trombe walls. Together they can encourage hot air removal from indoor spaces and promote air exchange between the built-up, hot indoor air and the cool outdoor air. This strategy operates as the cool air flows into buildings through tunnels located within the floor or foundation. The double-layer floors together with double-layer walls form a thermal-siphon. Diurnal temperatures differences in Khartoum are large enough that cool, night air can be stored in the floor and wall cavities and as building interior spaces warm up during the day, the siphoning effect can draw the cooled air into the interior spaces without the need for mechanical cooling systems. This strategy may perform better in Khartoum if the building's interior spaces are well protected from direct solar radiation and the fenestrations are designed and positioned to take advantage of cool outdoor air. Furthermore, the manner in which the architect adjusts the exterior landscape, courtyards, and building's interior space determines the extent of this strategy's success.

6.1.4. Wind towers

Wind towers have been used to provide cooling effects on building

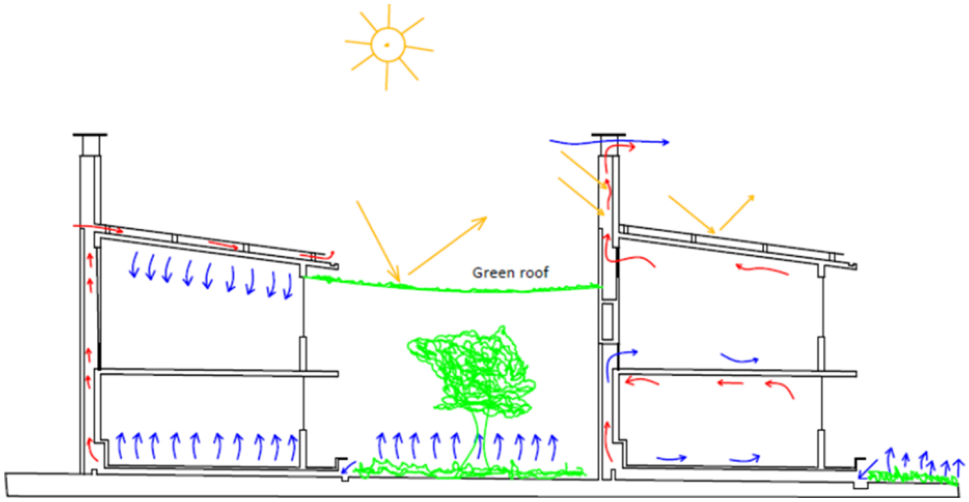

Fig. 11. Use of solar chimneys with trombe walls encourages creation a pleasant microclimates with trees, shrubs, and vines providing shading and natural ventilation and making air conditioning systems redundant.

interiors in hot, arid regions for centuries. Wind towers face challenges when used in dense urban areas where local airflow is invariably affected by the arrangement of buildings. In desert regions, wind towers face dust-sand storm phenomenon and their heights should be adjusted to rise above the level where winds carry most of the sand and dust. With the latter adaptations, construction and maintenance costs increase [Calautit, Chaudhry, Hughes, & Ghani, 2013].

Wind towers shows in (Fig. 12) operate in three ways. First, they direct prevailing winds downward from up high and toward building-interior spaces. The efficiency of enhancing building air quality with this strategy depends on exterior airflow rate. Second, wind-assisted temperature gradient strategy connects an underground tunnel to a tower with an opening facing away from the prevailing wind direction. When the tower is open, air is sucked upward and downwind by stack effect. The efficiency of wind-assisted temperature gradient strategy can be enhanced with evaporation cooling. Third, wind towers can work like solar chimneys when heated air in the tower rises through the opening encouraging cool air to move into building interiors from other fenestrations or vents [URL6 and Pallavi, 2014; Ahmadikia, Moradi, & Hojjati, 2012]. However, in situations where by there is high diurnal temperature difference, wind towers of mud-brick are cooled by radiation and convection [Ahmadikia et al., 2012].

Wind towers operate well in Sudan's hot season when temperatures exceed 40 °C and wind movement in the city is from south to southwest. Filtration of airborne particles should be controlled then because hot-season winds carry fine dust. Wind speeds increase during the night and help cool the air.

In the wet season, the wind movement is from southwest to north-northeast, probability of sand-dust storms is higher, and thermal comfort is least achievable. For this season, wind towers can offer adequate cooling from late evening to the early-morning hours.

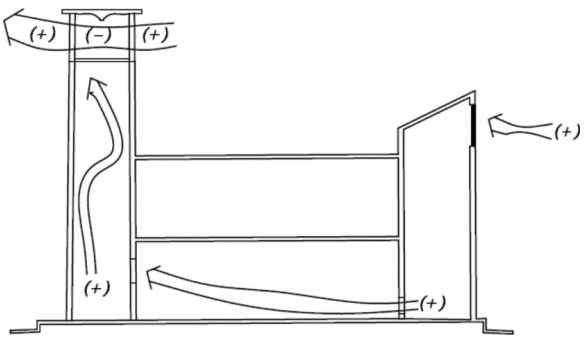

Fig. 12. Shows how windtower in Sudan operates in relation to prevaling wind direction.

6.1.5. *Sudanese adapted wind tower*

The type of wind tower traditionally used in Sudan is the one open-side type that has challenges associated with sand-dust storm and insect penetration. These challenges have been addressed in the adapted-Sudanese wind tower. This wind tower adaptation is employed on the Emergency NGO Pediatric Clinic, a low-rise building in the city of Nyala in western Sudan. The wind tower operates by capturing air from an 8-meter high tower, as in (Fig. 13a), and channeling air into the basement through a labyrinth. The labyrinth helps reduce air speed, the air is further cooled through the earth's thermal mass, and airborne sand and dust are deposited as the air slows. Finally, before entering the building's interior spaces, the air is treated by an industrial cooler (Fig. 13b).

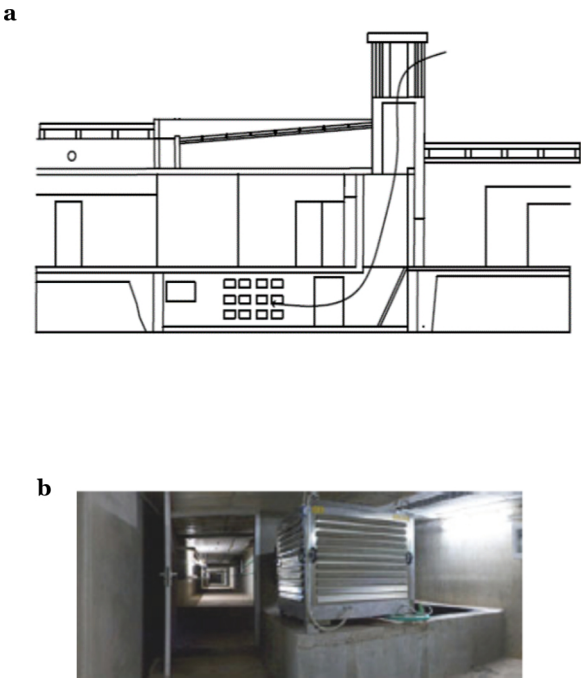

Fig. 13. Wind tower operates by capturing air from an 8-meter high tower Nyala clinic. Sudan (adapted from studio tamassociati). Air treatment by an industrial cooler.
Source: (courtesy of studio tamassociati).

This cooling strategy helps reduce air temperature by 10 °C and reduces usage of conventional air-conditioning by 70%. This cooling strategy could also be utilized in Khartoum in low-rise residential buildings except that it is not cost efficient for use in the center of the city where land prices are high; it can be better used away from the city center. Furthermore, wind towers could be enhanced for future buildings of Khartoum by adding evaporative cooling effect and using filters to control sand-dust storm, this way a reduction in cooling load could be achieved.

6.2. Heat-gain minimizing strategies

6.2.1. Solar control

Khartoum, Sudan is located in a region characterized by high solar-radiation intensity during its hot and wet seasons [El sheikh, 2015]. These characteristics should be considered in order to control sun exposure and avoid uncomfortable building-interiors during its eight-month-long hottest period. Khartoum has average monthly solar radiation of 27.55 MJ/m^2; it is considered to be the highest in the world [Omer, 1997]. In Khartoum, horizontal surfaces receive maximum solar radiation in the months of March, April, and May, coinciding with the hot season in which temperature exceed 40 °C during most of the time. During the dry season, the city receives less solar radiation [Sharag-Eldin, 1988].[5] According to Onsa, Onsa, Zamil, & Elzein, 2015, when building penetration of solar radiation is reduced by 20% to 40%, it leads to reductions in building thermal running costs by the same percentage [Onsa et al., 2015]. Consistent with Sharag-Eldin (1988) and supported by Climate Consultant's sun shading calculator, Khartoum buildings need appropriate shading from 9:00 AM to 5:00 PM during the hot and wet seasons. While in the dry season, shading from 10:30 AM to 3:00 PM is adequate [Sharag Eldin, 1988].

Based on the shading calculator analysis and Khartoum seasonal solar angle shows in (Table 5) south-facing windows receive direct solar radiation from August to April. Therefore, horizontal shading devices are required to obstruct inclined radiation at angle 51$^{0.}$ Furthermore, there is a need to obstruct inclined radiation through vertical fins from east and west at angle 43° and 45° respectively during morning and hot afternoon.

Because of Khartoum's location at 16° north, it receives solar radiation from the north between May and July; a little effort is encouraged to shade northern windows with roof overhangs. East and west side façade windows can be shaded with vertical, moveable fins. To address high solar intensity, a combination of both vertical and horizontal (egg-crate) shading patterns is most appropriate. Again, the Emergency NGO Pediatric Clinic in Nyala exhibits good examples of solar control strategy. South façade window are design to be small and recessed to intersect morning and afternoon hot inclined solar radiation to avoid overheating as (Fig. 14). Automated or smart shading devices can more efficiently respond to solar angle. Unfortunately, though functionally better at reducing solar gain, these technological shading devices are not cost efficient.

To conclude solar control as the most important strategy in Khartoum, windows should be appropriately sized and designed to achieve optimal thermal comfort.

6.2.2. Thermal mass

Thermal mass moderates diurnal temperature differences between day and night as a suitable cooling strategy in arid regions [Meir & Roaf, 2002]. The efficiency of thermal mass to enhance building-interior thermal comfort depends on the material's ability to store energy and release it when needed. This process is governed by the properties of the materials which include its specific heat capacity, density, thickness, and conductivity [Ghattas, Ulm, & Ledwith, 2013]. Usually, massive-wall construction succeeds in maintaining building interior temperature, reducing cooling load. However, the thermal mass achieved from brick, concrete block, and stone, etcetera also have the ability to hold and transmit heat gained from exterior surroundings to indoor spaces. For thermal mass to function properly, effective ventilation strategies need to remove deposited heat from the building and stimulate the mass for further thermal moderation [Brambilla, Bonvin, Flourentzou, & Jusselme, 2018]. Khartoum experiences dry-season temperatures lower than comfort levels especially from 6:00 PM to 6:00 AM. Using high thermal mass could increase comfort levels (see appendix 1). According to Ghattas et al. (2013), use of thermal mass in hot, arid climates achieves an annual savings of 4.9% in cooling load. This strategy is efficient in Khartoum only during the dry season. Furthermore, nowadays with the advancement in building construction technology innovative light weight phase change materials could be adapted for future buildings of Khartoum to enhance thermal mass without a need to add extra load on buildings. The benefits of using high thermal mass includes reduction in annual energy demand, adequate indoor quality, good acoustic and insulation properties, enhancing fire resistance of buildings, reducing insulation costs and reducing maintenance cost respectively [Ahmed, Khan, Oo, & Rasul, 2014].

6.2.3. Use of thermal insulation

Thermal insulation systems are used on building to reduce heat flow through buildings fabric. The performance of thermal insulation material is measured through thermal conductivity and thermal transmittance of the material also known as U value. For the material to serve as a thermal insulation, its conductivity should be lower than 0.07 W/mK. [Asdrubali, D'Alessandro, & Schiavoni, 2015]. The introduction of sustainability notions in recent decades necessitates utilization of thermal insulation as building envelope accounts for 40–45% of the building total thermal load [Omer, 1997; Hosseini & Akbari, 2014]. Using thermal insulation for walls and roofs helps reduce heat gain through the building envelope [Bhikhoo, Hashemi, & Cruickshank, 2017]. According to Sharag-Eldin (1988), using 5 cm thickness of expanded Polystyrene thermal insulation on exterior walls in Khartoum helps reduce radiated heat transfer between the two lines of brick wall. A great reduction in total heat flow can be achieved this way. The following (Fig. 15) shows a typical exterior insulated brick wall.

Khartoum buildings receive intense solar radiation between April and September and the greater part of the radiation falls on horizontal surfaces. For this reason it is very important to use thermal insulation on roofs to reduce cooling load. East- and west-facing vertical walls also receive a substantial portion of radiation therefore exterior thermal insulation should be used on exterior walls as well. There is not much research about thermal insulation in Sudan; the only known application shows thermal insulation (Fig. 16) used at the Slam Center for Cardiac Surgery in Khartoum. This building is a renowned climate-responsive, low-rise building. Most of high-rise buildings are designed and constructed without accounting for thermal insulation therefore air conditioning is frequently required to achieve thermal comfort.

6.2.4. High reflectance coatings for buildings

The latest progress in passive-design strategies contributes to reduced indoor temperatures by applying highly-reflective coatings. These coatings for buildings represent easy and cost effective solutions and may be applied to horizontal or vertical surfaces though rooftop application is most common. This strategy is most appropriate for low-rise buildings of Khartoum which receive maximum solar radiation on their horizontal surface from March to November. Santamouris, Pavlou, Synnefa, Niachou, and Kolokotsa, (2007) advocated use of this strategy in Khartoum's residential buildings to save 25.4% of the cooling load [Santamouris et al., 2007].

For this cooling strategy to function ideally, the reflectance coatings must have high reflectance across the solar spectrum, be easy to clean, durably maintain the original color, and resist ageing. Cleanliness may

[5] See solar radiation component diagram in appendix 4.

Table 5
Solar angle for Khartoum city of Sudan on monthly basis.
Source: Solar Electricity Handbook 2017 Edition Available at: http://solarelectricityhandbook.com/solar-angle-calculator.html (Accessed on 22 May 2018).

Month	Jan	Feb	March	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Solar angle in degrees	58	66	74	82	90	98	90	82	74	66	58	50

Solar angles for Khartoum city of Sudan on Monthly basis.

Fig. 14. Shows vernacular solar control system.
Source: (courtesy of studio tamassociati)

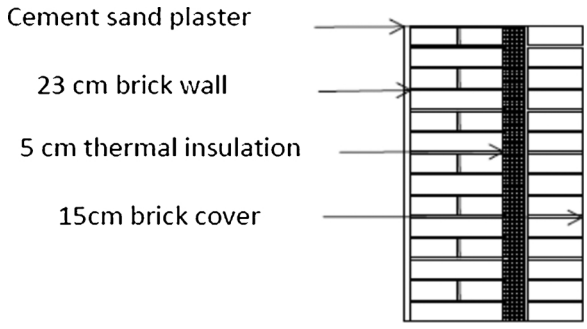

Fig. 15. Typical brick wall in Khartoum. Adapted from Sharg-Edin (1989).

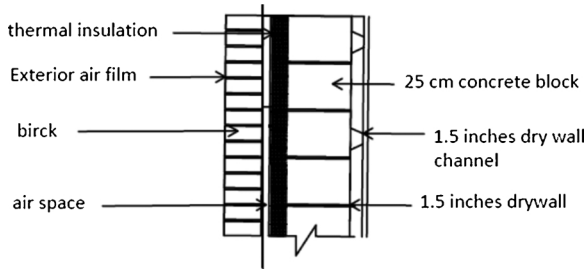

Fig. 16. Show thermal insulation adapted in Slam Center for Candiac Surgery, Khartoum.
Source: (courtesy of studio tamassociati)

be the most difficult aspect for roofs of Khartoum's buildings because of the historically-recognized preponderance and climate change-induced intensification and increased frequency of sand-dust storm [Zinzi & Fasano, 2009].

Although highly-reflective roof coatings reduce interior cooling loads, they bring the disadvantages of increased heating demand in the cooler, drier winter season; and reflectivity on low-rise buildings can cause visual discomfort (glare) for occupants of adjacent high-rise buildings [Dabaieh, 2015; Hosseini & Akbari, 2014; Taleghani, Tenpierik, van den Dobbelsteen, & Sailor, 2014]. In the case of Khartoum, the cool-season disadvantage is minimized due to the fact that the dry (winter) season is relatively short. Furthermore, these strategy could be innovatively used for Khartoum high rise and low rise building's roof and walls to reduce cooling load.

6.3. Sustainable active-cooling systems

Dabaieh, Wanas, Hegazy, and Johansson, (2015) calculated that about half of power usage is for air conditioning to meet cooling demand in hot and arid regions and Tong et al. (2014) pointed out that power consumption for air-conditioning reaches its maximum load during the summer period. These researchers and others acknowledge the fact that decreasing demand for air-conditioning is one of the greatest means of saving energy [Dabaieh et al., 2015].

Besides the use of passive-design strategies to reduce demand, it is expected that sustainable active-cooling systems will continue to increase their energy and cost efficiency until 2070 while simultaneously reducing their carbon footprint. Because Sudan has abundant solar energy potential with average daily sunshine lasting 8.5 to more than 11 h, sustainable active-cooling systems using renewable energy are a viable option [El Zein, 2017]. Such systems may have desiccant solar assisted cooling and heat pumps appropriate for Khartoum's hot (summer) season.

Conventional air conditioning requires steady and large quantities of power and should be paired with clean energy sources for sustainability. While Sudan's solar energy supply can adequately meet cooling demands using conventional systems during its 11-plus hour summer days, Magzoub and Osman (1998) conducted research in Khartoum demonstrating more efficient power usage for solar cooling of a brick building using solar simulation programs. Their finding shows it is possible to achieve up to 65% cooling of the brick building [Magzoub and Osman, 1998].

6.3.1. Desiccant air conditioning

Desiccant air conditioning can be used as a substitute for conventional vapor compression air-conditioning systems. Desiccant-system advantages over the later include its accessibility, cost effectiveness, and sustainability. This cooling system can be powered by solar energy,

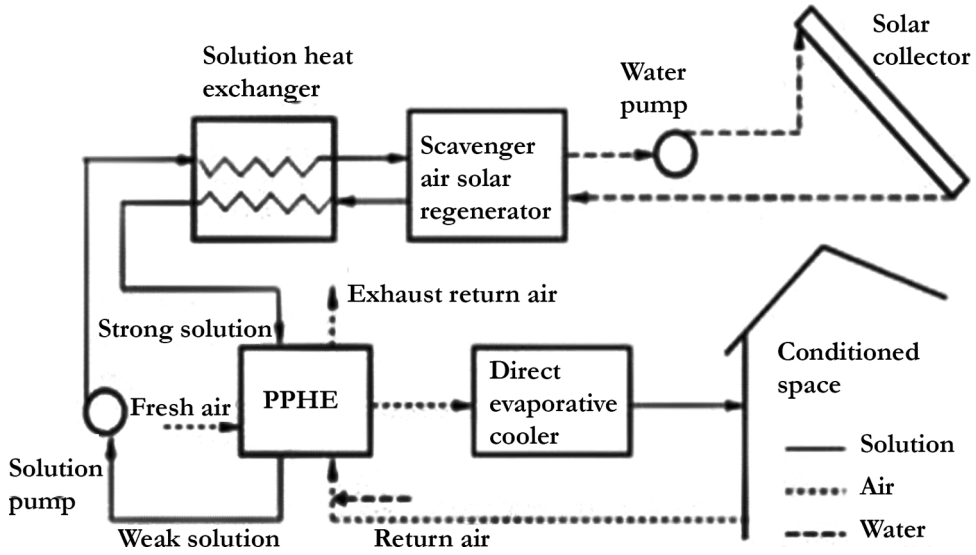

Fig. 17. Solar liquid desiccant air conditioning system.
Available at http://solarenergyengineering.asmedigitalcollection.asme.org/article.aspx?articleid=1474029#. (Accessed on 25 May 2018).
(Source: Alizadeh, 2008)

such that appreciable operating costs will be achieved [Concina, Sadineni, & Boehm, 2011]. Research conducted on solar-powered desiccant cooling utilization proves savings in all climate types [Daou, Wang, & Xia, 2006]. A research done by Abdalla and Osman (2017) on desiccant air conditioning powered by solar energy from evacuated-tube solar collectors can provide cooling load demand for the building for about 10 h [Abdalla & Osman, 2017]. However, as in appendix 3, active cooling is also demanded in Khartoum's wet season to achieve optimal thermal comfort. (Fig. 17) is a diagram of desiccant air conditioning powered by solar energy.

6.3.2. Heat pumps

Heat pumps can be used to provide heating, cooling and hot water for domestic use in all types of buildings. As well, they can be used in all climates because they take on earth's constant temperature for operation. There is a need to control and minimize refrigerant leakage through appropriate installation for environmental and appliance-maintenance purposes [Greening & Azapagic, 2012]. The efficiency of heat pumps is expressed as the Energy Efficiency Ratio (EER) [Manzella, 2017]. Besides the efficiency of the appliance, heat pumps depend on other factors which greatly contribute to the overall system efficiency. These factors include temperature level of the heat source and heat dissipation, and appropriate design and installation in accordance with the unique conditions of the area [Forsén, Boeswarth, Dubuisson, & Sandström, 2005].

Heat pumps can be divided into ground-source heat pumps (GSHP), groundwater-source heat pumps (GSWHP), and air-source heat pumps (ASHP) [URL7]. A ground-source heat pump (GSHP) is an adequate solution for heating and cooling residential and commercial buildings due to its energy efficiency compared with conventional air-conditioning systems [Jiang & Lei, 2017]. These systems are refrigeration machines that provide cooling and heating using stable underground or water temperatures [El sheikh, 2015]. GSHPs shown in (Fig. 18) can be divided into four systems.

1 Close loop: This system uses a buried loop containing water or a glycol solution to transfer the coolness to heat pumps and then to the building in hot areas [Valizadeh, 2013; Goetzler, Zogg, Lisle, & Burgos, 2009].
2 Vertical loop: This system involves bore-hole drilling to reach cool groundwater and transfer the coolness to the surface heat pump for distribution throughout a building. Vertical loop systems may be expensive in Khartoum due to the deep level of the water table [Valizadeh, 2013; Goetzler et al., 2009]. Horizontal loop: This system is less expensive because installation occurs only four to five feet below ground. Major disadvantages of this system are that it requires much land than the others, and it is more affected by seasonal temperature fluctuations [Valizadeh, 2013; Goetzler et al., 2009]. This system may not be appropriate for Khartoum's climate.
3 Hybrid system: This system is normally used in large buildings where cooling load is more than the heating load. In this system, the ground heat exchanger is replaced by a conventional cooling tower to cope with peak cooling load. This system has a reduced initial capital cost.

Groundwater-source heat pumps (GWSHP) are considered environmentally friendly and economically wise to use for heating and cooling buildings, and consequently have great potential to moderate greenhouse gas emissions [Kim & Nam, 2015]. This system exchanges groundwater coolness by draining heat from the pumps into the aquifer. This cooling system is efficient where groundwater is reliable and available without interruption throughout the year [Liu, 2017]. This cooling system is very effective for Khartoum because of availability and reliability of groundwater. The only disadvantage is the initial capital cost is relatively high. (See Fig. 19) shows different types of GWSHPs.

Air-source heat pumps (ASHP) are categorized based on their placement outside the heat exchanger by air to air and air to water [Staffell, Brett, Brandon, & Hawkes, 2012]. An air-source heat pump pull its heat indoors from the outdoor air in the winter as it functions as a heater and pushes indoor air out in the summer as a cooling system [URL 8]. ASHP technology has witnessed tremendous growth in recent years due to efficiency and reliability of pumps being used in the refrigeration cycle. Air-to-water heat pumps are efficient and environmentally friendly in reducing global warming. Air-to-air heat pumps are efficient in compact urban areas [URL9 and Lukanov, 2019] but their efficiency is less than ground-source and groundwater-source heat pumps [Ross, 2008]. (Fig. 20) shows ASHPs.

(Table 6) shows the advantages and disadvantages of heat pump types'. Heat-pump technology is a promising and sustainable technology, and if appropriately utilized would reduce the need for conventional air-conditioning systems which damage the environment.

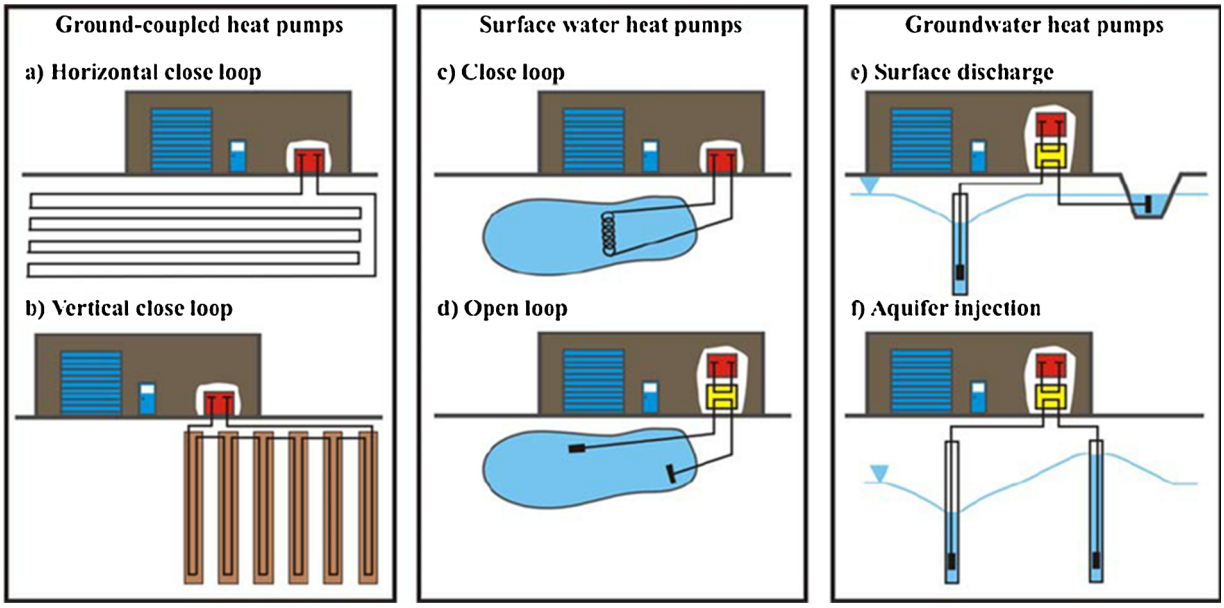

Fig. 18. Ground source heat pumps (GSHP) and their ground heat exchangers.
Source:[(Wright and Colvin (1993)].

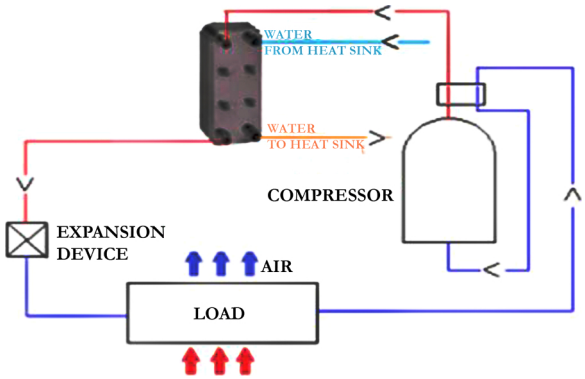

Fig. 19. Water source heat pump.
Avilable at: http://www.heat-pump-pro.com/watersourceheatpump.html.
(Accessed on 13 May 2018)
(Source: Water Source Heat Pump)

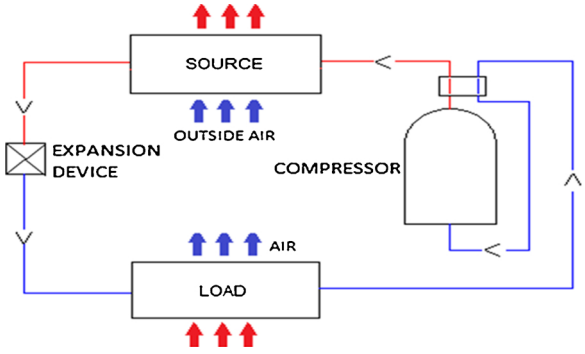

Fig. 20. Figure shows how Air source heat pumps (ASHP) works.
Source: (http://www.heat-pump-pro.com/airsourceheatpump.html)

This technology is not introduced in Sudan yet, and there are not enough experienced with its installation or use in Khartoum. From a literature survey on this subject matter, a reduction in capital cost can be achieved with hybrid and groundwater-source heat pump systems compared to ground-source heat pumps systems.

6.4. Dust-sand storm treatment for Khartoum's buildings

Air filtration issues have become more pronounced than ever before due to concerns about respiratory health [URL10, 2019]. Air filters are designed to remove dust concentrated in air where dust content of air does not exceed 2 mg (up to 0.2 mg) per cubic meter of air before entering HVAC systems [URL11, 2019]. The most common filter type used today is fibrous and is characterized as being 80–90% porous material with low resistance to air movement [Podgórski, Bałazy, & Gradoń, 2006].

6.4.1. Artificial air filters

According to Ahn et al. (2006), air filters can be categorized according filtration particulate efficiency as pre-filter, medium filter, high-efficiency particulate air (HEPA) and ultra-low particulate air (ULPA) [Ahn et al., 2006]. Pre-filters capture larger sand particles. Medium filters have an efficiency of 60–90%. HEPA filters are most sought after for air filtration in the building industry because of their 99.99% efficiency and their ability to trap air impurities of different diameter sizes. This filter type is appropriate for use in most public buildings like theatres and hospitals [Brincat et al., 2016].

ULPA filters have 99.999% efficiency [Ahn, Brincat et al., 2016]. These days, as air pollution rates increase, researchers are developing innovative new non-woven nano-fiber material that can perform even better in instances where the air contains smaller particle sizes [Wang et al., 2013]. Glass fiber is another excellent air filter which has efficiency of 99% [John & Reischl, 1978]. A trombe wall filter, shown in (Fig. 21), is an efficient filter and can provide qualitatively healthy ventilation for building interiors, especially in dense and contaminated urban centers like that of Khartoum [Imbabi, 2006].

6.4.2. Natural air filters

An active living wall (ALW) is a technology appropriate for buildings in which mechanical and natural ventilation is incorporated as in (Fig. 22). The system operates by forcing air to pass through the ALW, taking on the benefits of the AWL's biological capacity to cool, purify, and humidify air [Podgórski et al., 2006; Liu et al., 2017]. Bio façades are a new, innovative filtration strategy (Fig. 23). This filtration system could pave the way to more sustainable and environmentally friendly cites. According to Antony Wood, Bahrami, and Safarik, (2014), bio

Table 6
Advantages and Disadvantages of Heat pumps types.

Heat pump type	Advantages	Disadvantages
Ground source heat pumps (GSHP)	-Energy efficient -Cost effective with pay back of 2-10 years -have no visible sense -silent make no noise -low maintenance cost -pipes lasted for 40-50 years -adaptable in all climates -fire resistant -few moving part -more expensive than (GWSHP) &(ASHP but more efficient than them [URLQ]. -has better seasonal efficiency than (ASHP) [URLQ].	- lack of confidence in the technology - inadequate information about it -lack of adequate supply and services -uncertainty about actual average efficiency and published confidence of performance
Water source heat pumps (GWSHP)	-Suitable in all climates -cost effective -environmentally friendly -if properly designed can reduce cost -consumes less power if ground and water temperature remain constant throughout the year [Kim & Nam, 2015]. -few moving part	-depend on ground water temperature -more power used for pumping -local legislation -lack of knowledge -can effectively be used only where ground water is grantee [Kim & Nam, 2015].
Air source heat pumps (ASHP)	-energy efficient -economically wise -easy to retrofit in to existing buildings -does not need much external land for installation -appropriate in high dense urban areas -good for heating, cooling and water heating -long life span -easy maintenance	- need highly trained expert for installation -any leakage of refrigeration system hazard to the environment and can also damage the entire system -Less efficient than (GSHP) & (GWSHP)

The advantages and disadvantages of heat pumps types.

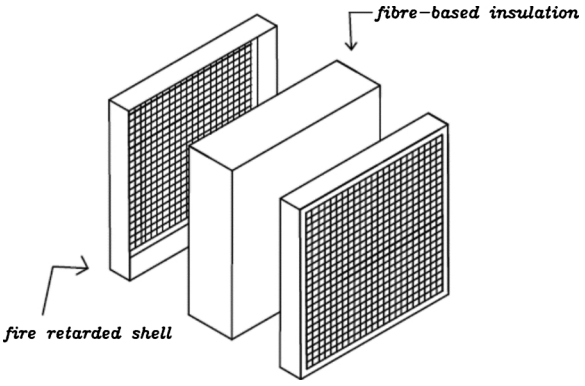

Fig. 21. Modular breathing panels in framed construction courtesy of EBP Ltd. (trombe wall).Source from: Imbabi (2006).

façades have numerous advantages at both the city and the building scale which are listed in (Table 7) [Wood et al., 2014].

6.4.3. Contemporary control systems for dust and sand control in Sudan

Currently, only two methods are used to control dust or sand from storms in Sudan's buildings. First, an adaptation to wind towers is derived from Iranian vernacular architecture where sand and dust fall out of the air when air shifts direction in the system. Here, fine particles are captured by the spraying of water. Second, air is allowed to pass through long underground tunnels constructed in labyrinthine ways to reduce airspeed and allow large particles to settle out of the air. Later, sprays of water control fine dust particles and cool down the air.

After review of these dust-control strategies, the following results are obtained. Non-fibrous filters (HEPAs and ULPAs) are valuable for their high efficiency but their disadvantage is high initial cost. Trombe walls, active living walls, and bio-façade filtration systems are good for their numerous advantages and adaptable for Khartoum buildings. Wind towers and underground tunnel systems have high initial cost and their construction requires additional land therefore they are not an economical choice for Khartoum.

7. Future scenario of building climate-responsive design strategies for Khartoum in the year 2070

Climate change is one of the greatest challenges facing humanity currently. It is widely accepted that the effects of greenhouse gas emissions on global climate indicate that energy consumption in buildings should be reduced and building should be able to resist climate change effects for a long time. However, this requires contemporary and future buildings to cooperatively function under extreme changing weather conditions [Guan, 2009]. Future projections of climate are inevitable and beneficial to achieving sustainable development for the current and future buildings.

7.1. Comfort model as applied in the year 2070

Climate change poses a significant challenge to human existence especially in hot, arid regions. It is imperative for architects to know about predicted future thermal performance of buildings; however, there is scarcity of climate data in most developing countries that is suited for prediction models [Jentsch, Patrick, James, & Bahaj, 2010]. This data scarcity was resolved through the use of building energy simulation (BES) program [Jentsch et al., 2010; Khalfan & Steve, 2016]. The program uses hourly weather file data to calculate thermal comfort and thermal performance of buildings [Remund, Müller, Schilter, & Rihm, 2010]. The most common weather file format is the Energy Plus Weather (EPW) file which can be either freely downloaded or obtained from Meteonorm Company. Future weather files can be obtained from weather generator software such as Meteonorm [Remund, Kunz, & Lang, 1999].

Future climate-change scenarios for Khartoum in the year 2070 is chosen on the basis of scenario $^{8}EU2C^{3}$ assumptions [Rasmussen, 2012]. Due to improvements in building and construction technologies,

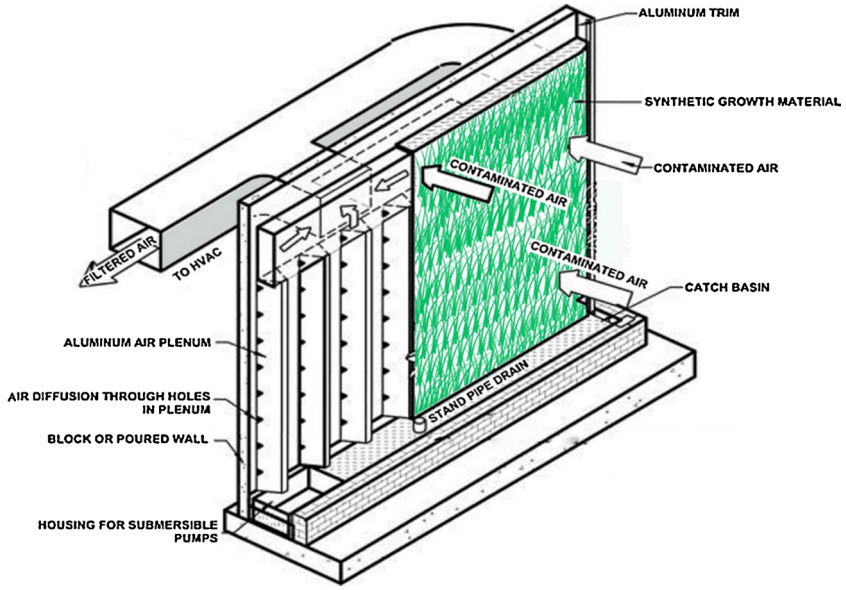

Fig. 22. Schematic of indoor biofiltration system.
Source from: Soreanu, Dixon, and Darlington (2013).

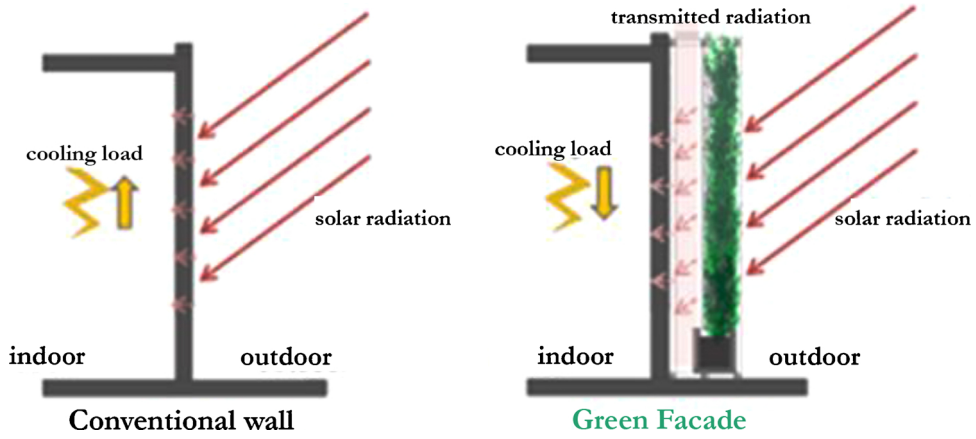

Fig. 23. Bio facade is a newly innovative filtration strategy.
(Source: Abdullahi & Alibaba, 2016).

building lifespans can extend to 80 and 100 years or more. So, predicting the next 55 years of climate-responsive building strategies is rationalized. Meteonorm 7.2.1 software was used to create weather files for Khartoum's 2070[6,7] . Together, these make it possible to calculate the 2070 weather file for Khartoum in order to evaluate how the future forecasted climate-responsive design strategies for the city would perform. (See Fig. 24) gives the rate of thermal comfort in Khartoum for the year 2070. ASHRAE Standard 55-2010 is again used for this research work. The result achieved for annual thermal comfort of Khartoum buildings without using any design strategies is 11.7% or 1023 h out of 8760.

With monthly thermal comfort values in mind and using ASHRAE 55-2010 as in (Table 8), Khartoum's dry season has the highest thermal comfort with December having the highest value of 30.6%. For the hot season, March has the highest thermal comfort with remaining months reaching 0%. The wet season is considered to be the hottest, and the highest thermal comfort that could be achieved is only 1.1% in October. Again the remaining months of this season have 0% thermal comfort. Based on these statistics, it will difficult to achieve thermal comfort in the hot and wet seasons without using design strategies in the year 2070.

7.2. ASHRAE standard 55 and current handbook of fundamental model

When ASHRAE Standard 55 and current Handbook of Fundamental Model is applied for the future climate of Khartoum, the maximum thermal comfort that can be achieved is 15.9% compared to 11.7% which was obtained when only the ASHRAE 55-2010 model was used. This variation may be attributed to the fact that this model used global horizontal radiation and relative humidity which is likely affected by the phenomenon of climate change as justified in this research.

Classifying climate-responsive strategies on a seasonal basis (Table 9), to represent the future climate of Khartoum in 2070, indicates that 36.6% thermal comfort can be achieved in the dry season, 13.7% in the hot season, and 0.9% in the wet season.

[6] Meteonorm version 7.2.1 can calculate future weather files up to the year 2100.

[7] Scenario [8]EU2C[3] assumes a world-wide implementation of a large reduction of the emission of greenhouse gasses. Industrial countries reduce their emissions of greenhouse gasses by 80-95%by 2050 compared with 1990 emissions. Consequently global warming will be limited to a maximum of 2C° (Nakicenovic et al. 2000. (Denmarks Meteorologikse institute 2010).

Table 7
Advantages of bio facade system both at city and building scale.
Source: [Wood et al., 2014].

Urban Scale	Building Scale
Reduction of the Urban Heat Island Effect	Improvement of Building Energy Efficiency
Improvement of Building Energy Efficiency	Internal Air Quality, Air Filtration and Oxygenation
Sequestering of Carbon	Health Benefits
Aesthetic Appeal	Envelop Protection
Psychological Impact on Urban Dwellers	Interior Noise Reduction
Providing Biodiversity and Creating Natural Animal Habitats	Agricultural Benefits
Sound Deadening	Increasing Property Value Sustainability Rating System Credits

Advantages of bio facade system both at city and building scale.

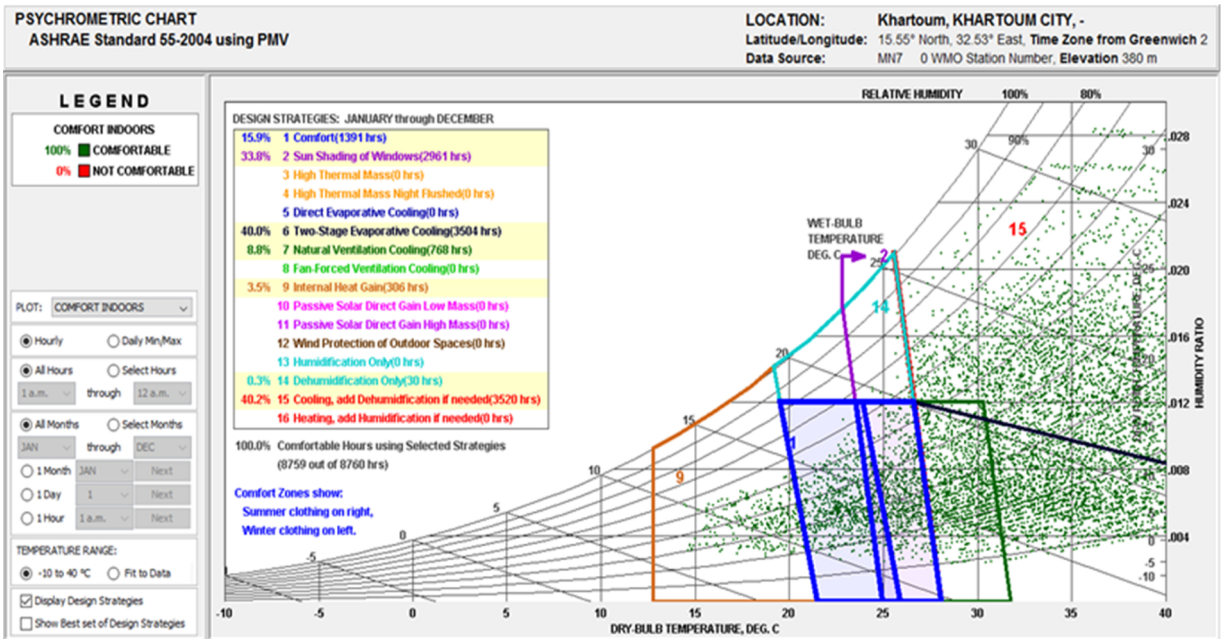
PSYCHROMETRIC CHART
ASHRAE Standard 55-2004 using PMV
LOCATION: Khartoum, KHARTOUM CITY, -
Latitude/Longitude: 15.55° North, 32.53° East, Time Zone from Greenwich 2
Data Source: MN7 0 WMO Station Number, Elevation 380 m
LEGEND
COMFORT INDOORS
100% COMFORTABLE
0% NOT COMFORTABLE
DESIGN STRATEGIES: JANUARY through DECEMBER
15.9% 1 Comfort(1391 hrs)
33.8% 2 Sun Shading of Windows(2961 hrs)
3 High Thermal Mass(0 hrs)
4 High Thermal Mass Night Flushed(0 hrs)
5 Direct Evaporative Cooling(0 hrs)
40.0% 6 Two-Stage Evaporative Cooling(3504 hrs)
8.8% 7 Natural Ventilation Cooling(768 hrs)
8 Fan-Forced Ventilation Cooling(0 hrs)
3.5% 9 Internal Heat Gain(306 hrs)
10 Passive Solar Direct Gain Low Mass(0 hrs)
11 Passive Solar Direct Gain High Mass(0 hrs)
12 Wind Protection of Outdoor Spaces(0 hrs)
13 Humidification Only(0 hrs)
0.3% 14 Dehumidification Only(30 hrs)
40.2% 15 Cooling, add Dehumidification if needed(3520 hrs)
16 Heating, add Humidification if needed(0 hrs)
100.0% Comfortable Hours using Selected Strategies
(8759 out of 8760 hrs)
Comfort Zones show:
Summer clothing on right,
Winter clothing on left.
RELATIVE HUMIDITY
WET-BULB TEMPERATURE DEG. C
HUMIDITY RATIO
DRY-BULB TEMPERATURE, DEG. C

Fig. 24. Shows Psychometric chart with climate responsive Design strategies applied in Khartoum city for the 2070.
(Source; Author).

Table 8
Adaptive Comfort Model in ASHRAE Standard 55- 2010 applied to Khartoum City Sudan for the monthly thermal comfort for the year 2070.

Months	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Comfort %	11.7%	27.7%	28.3%	25.3%	0%	0%	0%	0%	0%	0%	1.1	28.2%	30.6%
Comfort hrs.	1023	206	190	188	0	0	0	0	0	0	8	203	228
Total hrs.	8760	744	672	744	720	744	720	744	744	720	744	720	744

Adaptive Comfort Model in ASHRAE Standard 55—2010 applied to Khartoum City Sudan for the monthly thermal comfort for the year 2070.

Table 9
Shows the design strategies for seasonal thermal comfort for Khartoum City of Sudan for the year 2070 using ASHRAE Comfort Model 55.

Design strategies	Dry Season	Hot Season	Wet Season
Comfort	36.6%	13.7%	0.9%
Sun shading	30.6%	36.3%	34.8%
Two-stage evaporative cooling	48.5%	74.9%	12.4%
Internal heat gain	10.5%	0.25	–
Heating, add humidification(active-heating)	–	–	–
Active cooling	4%	11.1%	86.1%
Dehumidification only	0.2%	–	0.7%
Natural ventilation	–	–	–

Shows the Design strategies for seasonal thermal comfort for Khartoum city of Sudan for the year 2070 using ASHRAE Comfort model 55.

The weather in the dry season is the most pleasant among all Khartoum's seasons. It is easy to achieve thermal comfort for building users by adjusting their clothing, and employing the most influential design strategies: internal heat-gain design strategies, dehumidification only and active cooling strategies. All these strategies have a direct effect on thermal comfort and they constitute 10.5% (301 h), 0.2% (6 h), and 4% (116 h) respectively. Two-stage evaporative cooling constitutes 48.5% (1396 h) and if not used would increase active cooling from 4% (116 h) to 37.4% (1076 h). Natural ventilation has little direct effect on thermal comfort and contributes only about 15.4% (443 h).

In the hot season, it might be difficult to achieve optimal thermal comfort without adapting active cooling; this strategy directly affects thermal comfort with an 11.1% (246 h) improvement in thermal comfort. Also, the internal heat gain contributes about 0.2% (5 h) to improve thermal comfort. Although two-stage evaporative cooling does

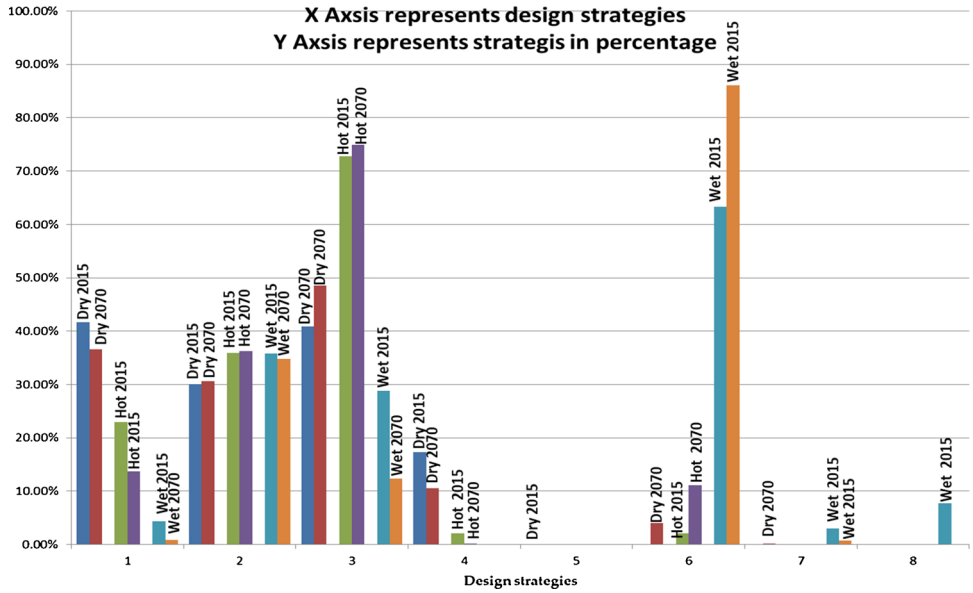

Fig. 25. Shows comparison of design strategies of 2015 and 2070 for Khartoum city, Sudan.
1 = Thermal Comfort.
2 = Sun shading.
3 = 2 stage evaporative cooling.
4 = Internal heat gain.
5 = Heating, Add Humidification.
6 = Cooling Add dehumidification.
7 = Dehumidification only.
8 = Natural Ventilation.

not directly affect thermal comfort, if not applied, the need for active cooling will increase from 11.1% to 86.1%. Therefore it is recommended that all these strategies should be incorporated in the future design of Khartoum buildings in order to avoid any excessive overheating that might occur.

Khartoum's wet season has the lowest thermal comfort without using other design strategies. Compared to the other seasons, thermal comfort conditions are only met 0.9% (33 h) in a year. In this season, cooling and dehumidification (active cooling) and dehumidification only, have direct effects on thermal comfort of 86.1% (3160 h) and 0.7% (24 h) respectively. Two-stage evaporative cooling has no direct effect on thermal comfort but if not used would increase the need for active cooling from 86.1% to 98.4%; therefore, it should be incorporated as an essential design strategy.

From the seasonal analysis of the 2070 hourly weather file, difficulty in achieving optimal thermal comfort for building users of Khartoum in the future is conclusive. Therefore there is a need for adaptation of sustainable active-cooling in all seasons of the year. The wet season is projected to have the lowest thermal comfort level while the dry season will have the highest thermal comfort compared to other seasons. Maximizing passive-design strategies is essential for all Khartoum's buildings and should be taken as a principle design strategy. Designers should start figuring out agreeable and sustainable solutions for energy-efficient active-cooling systems in order to save costs and reduce cooling load during the long, hot months in Khartoum. With maximal passive-design techniques and utilization of Sudan's abundant renewable energy sources then reduced usage of conventional active cooling systems may be observed. For example, two-stage evaporative cooling with solar cooling, heat pumps, and desiccant cooling assisted by solar energy optimal thermal comfort may be achievable in Khartoum, Sudan in the year 2070.

8. Results and discussion

Trends analysis of Khartoum climate data from 1981 to 2015 was conducted on a seasonal basis, the parameters studied were monthly relative humidity, average monthly temperature, average monthly wind speed, and average monthly rainfall. The analysis produced the following results:

- Relative humidity decreases in the dry and hot seasons, and increases in the wet season.
- Temperature increases in all the three seasons of the year.
- Wind speed increases in dry seasons and decreases in hot and wet seasons.
- Rainfall increased in dry and hot seasons and decreases in wet seasons.

These prove that climate change occurred in Khartoum between 1981 and 2015. Furthermore, climate is expected to exhibit the following characteristics in the future:

- Humidity will continue to decrease in dry and hot seasons and increase in wet seasons.
- Temperature is expected to increase in all seasons of the year.
- Wind speed will continue to decrease in hot and wet seasons while increasing in dry seasons.
- Rainfall will continue to decrease in wet seasons and increase during dry and hot seasons.

By comparing Khartoum's current monthly thermal comfort levels (Table 3) with future monthly thermal comfort levels projected for 2070 (Table 7), the following observations were made:

- Monthly thermal comfort in the year 2070 from April to September is zero, which indicates that it is impossible to achieve thermal comfort without using any design strategies.
- Annual thermal comfort will reduce from 24.2% in 2015 to 11.7% in the year 2070. This indicates that climate-change effects on 2070 Khartoum would be significant.

- Dry season months in the two scenarios 2015 and 2070 have better thermal comfort than other seasons while wet season months have the worst thermal comfort.
- All hot season months except March have thermal comfort of 0% in 2070.
- Thermal comfort for all months of 2070 is lower than for those in 2015 except December. December occurs in the dry (winter) season and improved thermal comfort in 2070 suggests that the temperature is warmer in December 2070 than December 2015.

By comparing design strategies of the year 2015 to those of 2070 (Fig. 25), ten results are observed.

1 The lowest future thermal comfort level (0.9%) achievable in Khartoum, Sudan, in the year 2070 is in wet season. The lowest thermal comfort level (4.3%) in the year 2015 was also obtained in the wet season. Hence, active cooling will be essential in 2070.
2 Solar shading of windows is an important design strategy in both contemporary and future designs.
3 Active cooling is an essential design strategy to achieve optimal thermal comfort levels in all seasons in the future 2070 climate of Khartoum, while it is essential only for the hot and wet seasons in 2015. Therefore, there is a need for sustainable cooling systems to reduce conventional air-conditioned cooling loads.
4 Natural ventilation and heating and dehumidification are no longer applicable design strategies in 2070.
5 Demand on internal heat-gain strategy is reduced in the dry seasons from 17.3% in 2015 to 10.7% in 2070 and should be avoided in hot and wet seasons in Khartoum's future.
6 Two-stage evaporative cooling is needed in all seasons in both 2015 and 2070 except that its need is reduced in the wet season of 2070 and sustainable active-cooling systems should be substituted.
7 Design strategies will change in the year 2070 by adapting to more active-cooling in all seasons except for the dry season when it can be minimized. Also, appropriate solar control design is necessary to avoid any overheating that might occur while solar heating is not needed.
8 In the future climate of Khartoum with appropriate weather control to reduce climate change and maximization of passive-design strategies such as evaporative cooling, natural ventilation, wind towers, solar chimneys and sustainable active cooling (desiccant and heat pumps), a reduction could be made in use of conventional air-conditioning systems which constitute a great part energy use in Sudan.
9 This research sought to find solutions for sand-dust storm problems which have become more frequent than ever before due to climate change in Khartoum. These storms constitute a source of discomfort and health problems for building's occupants.
10 The study examines various responses to sand-dust storms and façade solutions by turning to bio-façades and active living wall systems that are appropriate for their ability to control the symptoms of sand-dust storms and provide evaporative cooling effects.

9. Conclusion

This study examined Khartoum's 1981–2015 climate data through an extensive statistics analysis of trends on a seasonal basis. The findings proved that there has been change in Khartoum's climate.

Relative humidity has decreased in dry and hot seasons, and increased in wet seasons. Temperature increased throughout the seasons of the year. Wind speed increased in dry seasons and decreased in hot and wet season. Rainfall increased in dry and hot seasons and decreased in wet seasons.

Analysis of the contemporary hourly weather file of Khartoum is calculated by Meteonorm 7 from the average climate data obtained from Khartoum Meteorological station for the years 1996 to 2015. The weather file obtained is then run in computer software called Climate Consultant 6.0. From these, contemporary design strategies are obtained. Finally, these strategies are elaborated and their adaptation criteria in Khartoum buildings are explained.

Comparison of design strategies obtained from the two time series (2015 and 2070) shows that there is need to maximize passive-cooling design strategies. However, sustainable renewable energy resources in Sudan should be appropriately utilized to provide sustainable active-cooling in order to achieve optimal thermal comfort in the future.

Two-stage evaporative cooling should be used in all seasons together with sustainable active-cooling strategies assisted by solar energy such as (desiccant cooling, and heat pumps) in order to reduce the demand on conventional air-conditioning systems. Even though natural ventilation may only be applicable to some extent in the wet season, it should be enhanced through stimulating winds through a combination of wind towers and solar chimney strategies to save energy. Window shading is also a very crucial matter in Khartoum climate in all seasons of the year.

Filtration of sand and dust from storms is a very important strategy in all seasons since it occurs in all months of the year in Khartoum. This research work analyzed different alternative solutions and concluded that façade-based filtration such as active living walls and bio-façades might be a solution to control sand and dust for Khartoum's buildings.

Author contributions

Mobark Mohamed Osman and Harun Sevinc conceived and designed the paper outline. Mobark Mohamed Osman conducted the analysis and wrote the paper. Harun Sevinc supervised; provided sources, materials, and comments; and edited the paper.

Conflicts ofinterest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.scs.2019.101429.

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